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GENERAL ELECTRIC REVIEW

VOL. XXVIII, No. 7

Published by
General Electric Company's Publicity Department
Schenectady, N. Y.

JULY, 1925

AN INTERURBAN ELECTRIFICATION OPERATING ON 5-MIN. HEADWAYS THROUGH THE DAY. DECREASED TO 3 MINUTES DURING THE RUSH-HOURS

Direct-current, 600/1200-volt, two-car train leaving the Barcelona Terminus of the Cataluna Tramway System, Spain

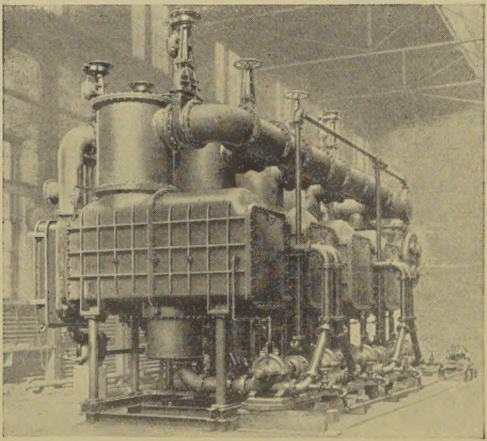
(See page 520)

In This Issue: ***Engineering Education*** ***Australian Automatics*** ***Single-phase Short Circuits*** ***A Spanish Electrification*** ***Over Voltage Due to Dropping Load*** ***Induction Motor Progress*** ***Charles A. Coffin Award*** ***Light Projection*** ***Short Cuts to Short-circuit Values***

Evaporators? -Yes!

PLANT AND LOCATION				BOILERS				SUPER HEATER		ECONOMIZERS				TURBINES								CONDENSERS									BOILER FEED WATER		
																						TEMPERATURE							PUMP				
NO.	NAME	CITY	STATE	TYPE	MAKE	TOTAL SURFACE SQUARE FEET	FLUE GAS PASSES	PER CENT BOILER SURFACE	DEGREES SUPER HEAT F.	TYPE	PER CENT BOILER SURFACE	CLEANING	DRAFT LOSS INCHES OF WATER	MAKE	NUMBER OF UNITS	SINGLE UNIT CAPACITY K.W.	SPEED R.P.M.	LBS. THROTTLE PRESSURE	TOTAL TEMPERATURE F.	BLEEDING POINTS	HEAT CYCLE	MAXIMUM	MINIMUM	NUMBER PASSES	FRESH OR SALT WATER SOURCE	SQUARE FEET PER K.W.	GALLONS PER SQUARE FOOT	TUBE LENGTH FEET	SPEED	DRIVE	SOURCE	EVAPORATORS	PER CENT MAKE-UP
10	PHILO	ZANESVILLE	OHIO	CROSS DRUM	B&W	14,090	2	17.9	250	SEPARATE	63	STEAM	1.25	GE	2	35,000	1800	530	725	2	RR	80	36	2	FRESH	1.30	1.30	21	CONSTANT	AC	RIVER	YES	2.0
11	SEAL BEACH	SEAL BEACH	CAL	DO	DO	25,450	3		256	—	—	—	—	WEST	1	35,000	1800	350	700	4	R	—	—	2	SALT	1.50	1.11	—		AC	SEA OR WELL	YES	1.3
12	TORONTO	TORONTO	OHIO	DO	DO	20,470	3	17.3	260	—	—	—	—	GE	2	30,000	1800	350	650	3	R	80	34	2	FRESH	1.67	1.20	20	VARIABLE	AC	RIVER	YES	3.0

16 of the 22 stations selected to represent American practice by P. Junkersfeld and G. A. Orrok use Evaporated Boiler Feed Make-Up



Our new catalog G-117, "WHEELER EVAPORATORS," includes a present-day study of the methods of correlating evaporators with other heat balance equipment used by the most modern power plants. Write today for your copy.

1,155,000 KW.

of Installed capacity is now protected by

WHEELER EVAPORATORS

in such Modern Power Plants as

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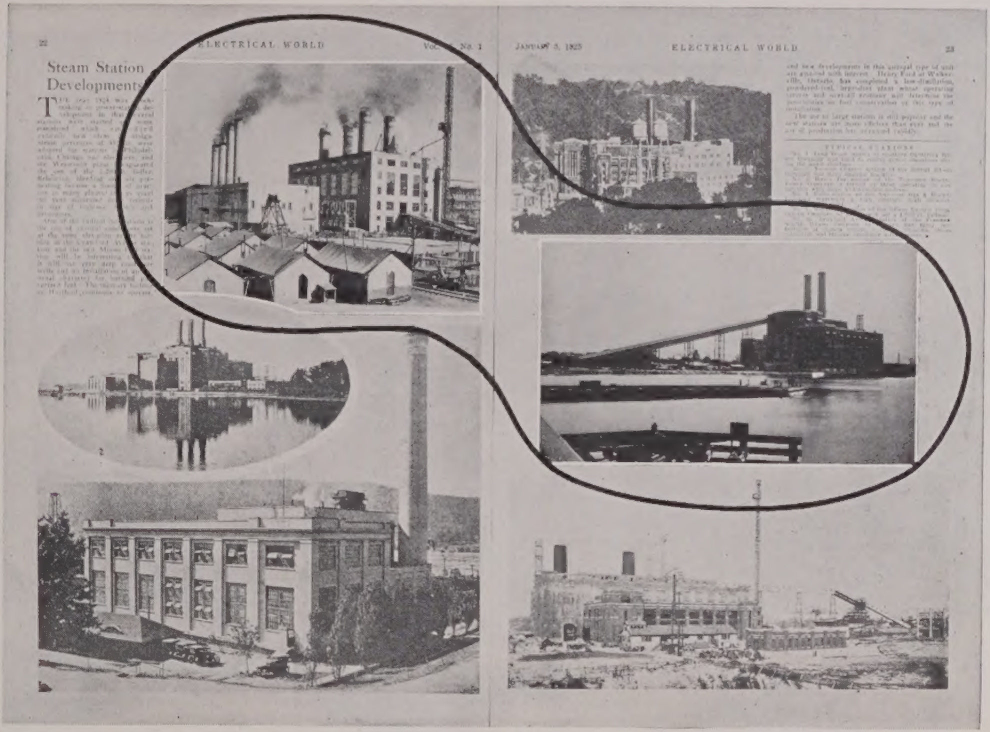


ONE-THIRD of the most notable power station work of last year as selected by ELECTRICAL WORLD was Stone & Webster work.

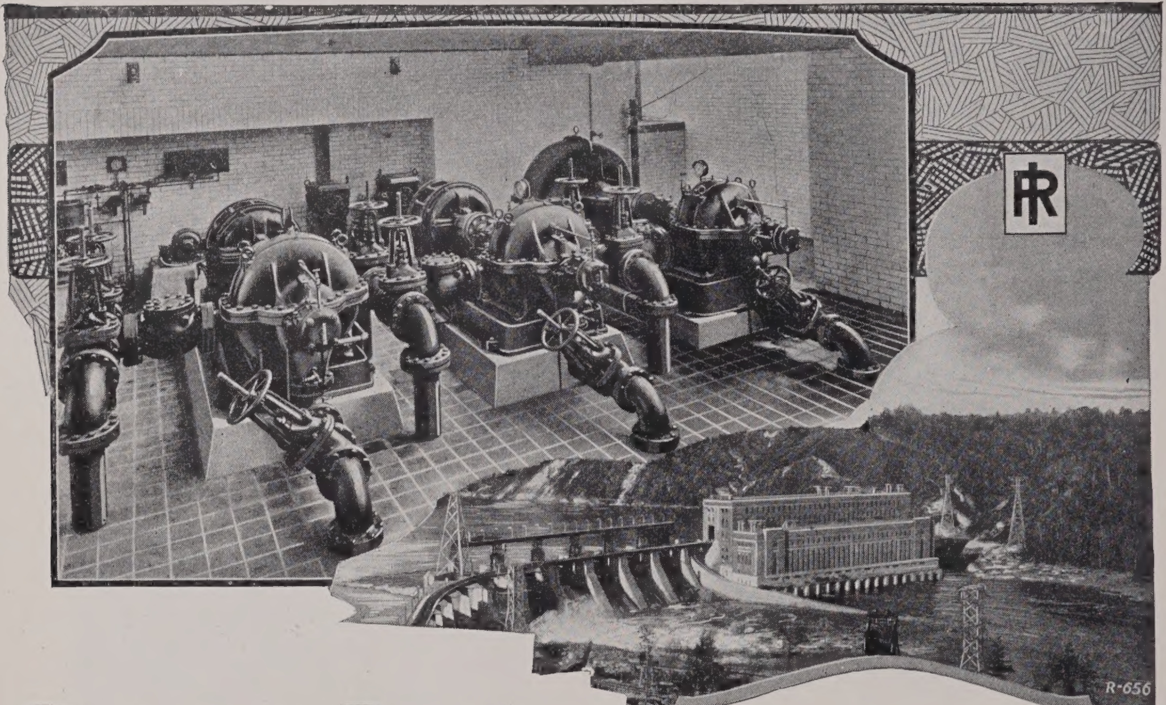
Their selection includes the Weymouth Station at Boston on the Atlantic Coast (right center) and the Long Beach Station at Los Angeles on the Pacific Coast (upper left).

STONE & WEBSTER
INCORPORATED

DESIGN · BUILD
OPERATE
FINANCE

NEW YORK, 120 Broadway
SAN FRANCISCO, Holbrook Bldg.
CHICAGO, 38 S. Dearborn Street
PHILADELPHIA, Real Estate Trust Bldg.
BOSTON, 147 Milk Street

WHERE RELIABILITY COUNTS



IR

R-656

Cameron Pumps

THESE three Cameron Multi-Stage Centrifugal Pumps are located in the governor pump pit, and supply water for the wheel controlling mechanism of the 30,000 horse-power turbines.

On just such exacting service as turbine control, you are always safe in relying on Cameron Pumps. Rugged and simple construction enables them to operate continuously month after month at their original high efficiency. Adjustments or repairs are required but seldom and when necessary, can be made quickly and economically.

The LaGabelle Development of the St. Maurice Power Co.

LaGabelle Rapids on the St. Maurice River is the site of an important development that has recently been completed.

The dam is 1,935 feet long and comprises 530 feet of spillway, 395 feet of sluice section, the power house structure and 638 feet of bulkhead section.

The present installation consists of four turbine-driven generators having a capacity of 33,000 kv-a.

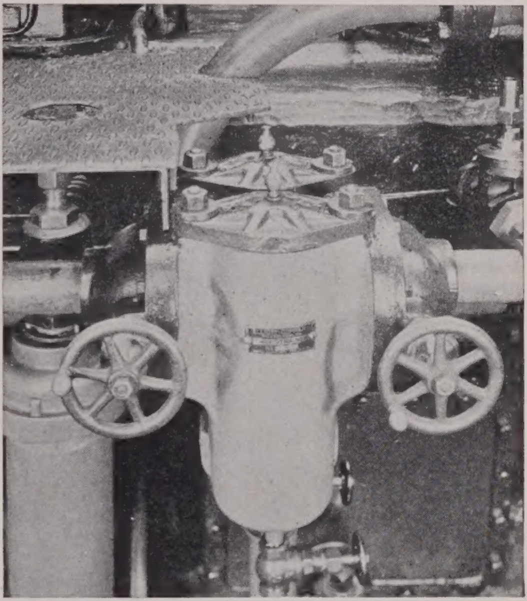
INGERSOLL-RAND COMPANY—11 BROADWAY, NEW YORK CITY
Offices in principal cities the world over
FOR CANADA REFER—CANADIAN INGERSOLL-RAND CO., LIMITED, 260 ST. JAMES STREET, MONTREAL, QUEBEC.

Ingersoll-Rand

A. S. CAMERON STEAM PUMP WORKS

Say you saw it advertised in the General Electric Review

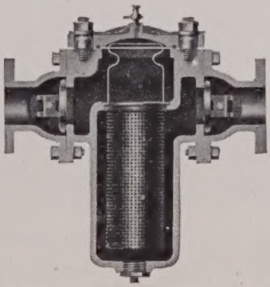
Strain the "Trouble" Out of Fuel and Lubricating Oil



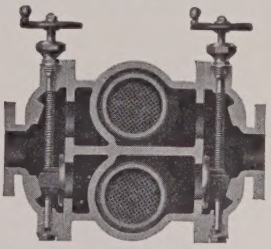
2-in. Twin Oil Strainer in the oil circulating line of a 30,000-kw. turbine. Philadelphia Electric Company, Delaware Station.

The flow of oil in lubricating lines or to fuel burners must be continuous. Interruptions or clogging means disaster.

With Twin Oil Strainers in the line, protection against clogging is assured. The flow of oil through the Strainers is not interrupted even in the process of cleaning the Strainer. One straining compartment is in service while the other may be opened and cleaned.



Vertical Section of Twin Oil Strainer. Inlet at the left



Horizontal section. Gate valves direct the flow to the basket compartment

ELLIOTT COMPANY

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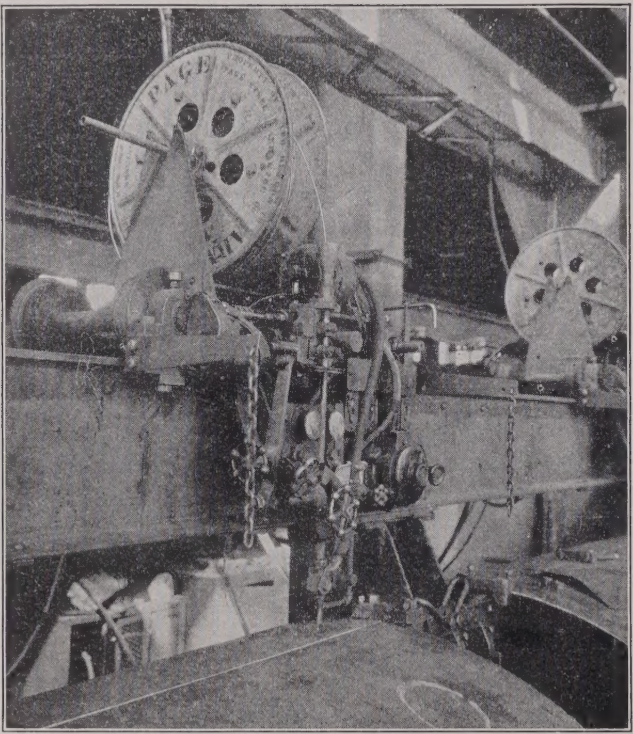
AA-117

TWIN OIL STRAINERS



What automatic welding *showed him about rods*

"When I found out by actual test that PAGE-ARMCO rods gave best results in my automatic welder, it started me thinking.

"Perhaps a good welder can do a fair job with less uniform, less free-flowing metal than PAGE-ARMCO, *but it must take him longer to do it*. If the poorer metal makes the machine stutter it must slow up the man.

"I'll pay a little more for an inexpensive thing like welding rods any day to save a welder's time. I'm confident we are now getting better work for *less money*."

Try PAGE-ARMCO. If you don't have the same experience, let us know. Mail us a card and we will send you an illustrated folder showing how good rods cut welding costs—and arrange for your PAGE-ARMCO test.

Page Steel and Wire Company

Bridgeport, Connecticut

District Offices: Chicago New York Pittsburgh San Francisco

An Associate Company of the American Chain Company, Inc., of Bridgeport, Conn.

MANUFACTURERS OF

RODS —Armco Ingot Iron and Special Analysis Steels

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FENCE—Woven Wire for Farm and Railway Right-of-Way, Page Hi-Way Guard, Wire Link Protection for Industrial Plants, Lawns, Schools and Estates, and Factory Partition.

PAGE-ARMCO

Welding Wire and Electrodes

The Lightning Storms of 1925 ?

An insulator is not immune to a direct lightning stroke. But Locke Insulators do combine many protective features which provide the highest factors of safety in the presence of extreme electrical disturbances

Locke Insulator spacing provides maximum protection
LOCKE
R = ∞

PROVIDE Locke Insulators for your next installation—both for new lines and replacements—and enjoy relief from lightning troubles and other harmful transients during summer storms.

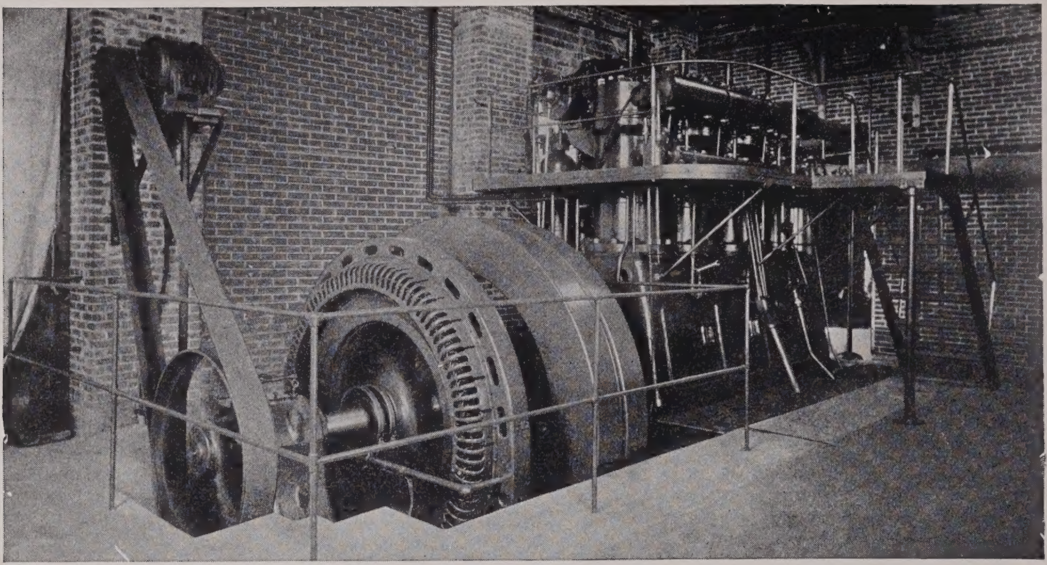
Locke Suspension Insulators are spaced a maximum safe distance apart to obtain maximum flashover value and protection against lightning.

The 5¾″ spacing between Locke Standard Suspension Insulators does not lead to excessive cascading from power arcs. It does not cause any excessive hazard nor reduction of safety factor against puncture.

Locke Standard Suspension Insulators have operated for many years with entire success, giving users maximum protection against flashovers for minimum costs.

LOCKE INSULATOR CORPORATION
Baltimore, Md., and Victor, N. Y.

LOCKE
PORCELAIN



Fuel consumption 0.1 gal. per kw. hr. for a small (225-kw.) generating outfit running with fluctuating load averaging 60%

THIS is the record made by a 300-b.hp. McIntosh & Seymour Diesel Engine during a year's 24-hr. per day operation in a small municipal plant in the Middle West.

The City Manager writes us:—

> "Our McIntosh & Seymour Diesel has sustained every claim your company made. We are much pleased and would not consider any other type of prime mover."

If you need more or better power in small or moderate amount and at a generating cost surprisingly close to that in a big central station, tell us your conditions and our Service Engineers will show you how. They will further refer you to long-time installations in which dependability, simplicity of operation and low fuel and maintenance expense are being demonstrated beyond question.

At least write for our literature.

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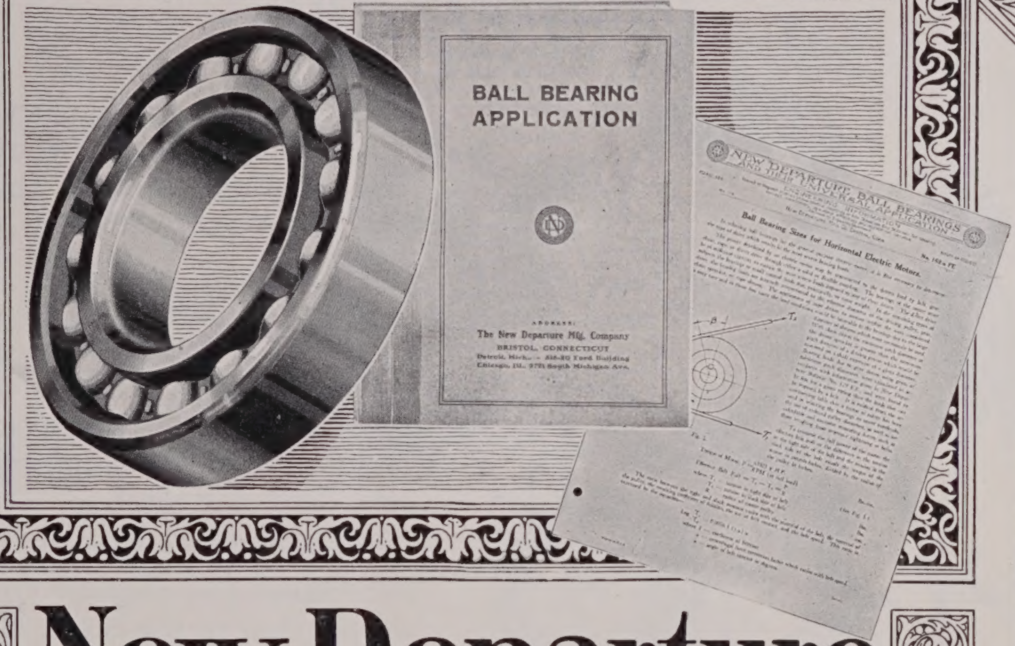
DIESEL ENGINES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BRISTOL, CONNECTICUT
NEW DEPARTURE BALL BEARINGS
Ball Bearing Sizes for Horizontal Electric Motors

New Departure Ball Bearings

"The Best Information I Have Seen on Ball Bearing Application"

SIMILAR remarks received daily convince us that the New Departure Engineering Reference Book is a work which every engineer and designer interested in improvement of product should have.

It consists of a loose-leaf binder with detailed description of New Departure types, general mounting directions, charts for calculating loads under various conditions, standard fits, methods of housing and enclosure for all conditions, telegraphic code and some 150 practical applications to different types of machinery, including 24 on the subject of electrical machinery.

To keep the work strictly up to the minute new data is issued monthly to add to or revise existing material.

Distribution of this data service is necessarily limited to those who can really use it to advantage. Therefore, use your Company letterhead and give official position in requesting.

THE NEW DEPARTURE MANUFACTURING COMPANY
Detroit Bristol, Conn. Chicago

186

Chattering's all right in its proper place

But that doesn't happen to be on the commutators of your motors and generators, nor on the rings of your rotary converters.

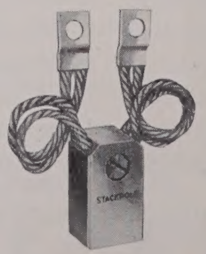
Chattering, sparking, electrical cutting and heating are all prevented by STACKPOLE Brushes. Their self-lubricating qualities eliminate brush noise and insure perfect commutation with minimum commutator and ring wear.

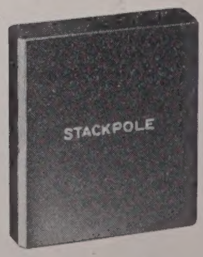
Specify STACKPOLE for whatever brush requirement you have in mind—they're the result of over 18 years' experience in manufacturing brushes of superior quality and utility.

Stackpole Carbon Company

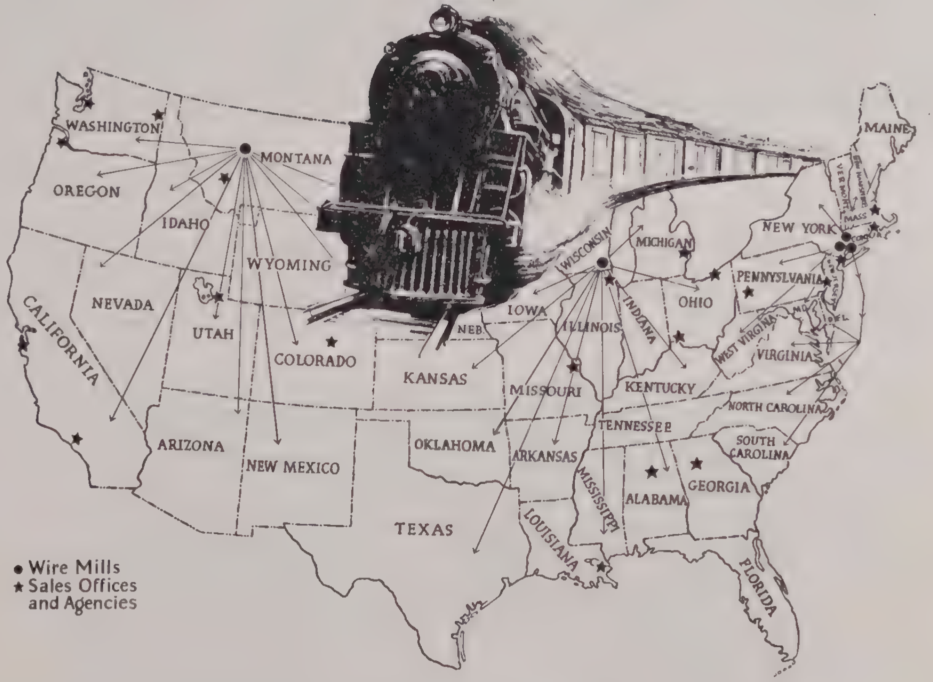
St. Marys Penna.

Stackpole carbon brushes





5 Wire Mills
at your service



The new Anaconda Wire Mill at Kenosha, Wis., rounds out Anaconda's unequalled facilities for nation-wide service on Copper Wire.

Anaconda Copper Wire Products include Bare, Weatherproof and Slow Burning Wire and Cable. Paper Insulated, Lead Sheathed and Varnished Cambric, Insulated Lead Sheathed or Braid Covered Power Cable, Copper and Hitenso Trolley Wire.

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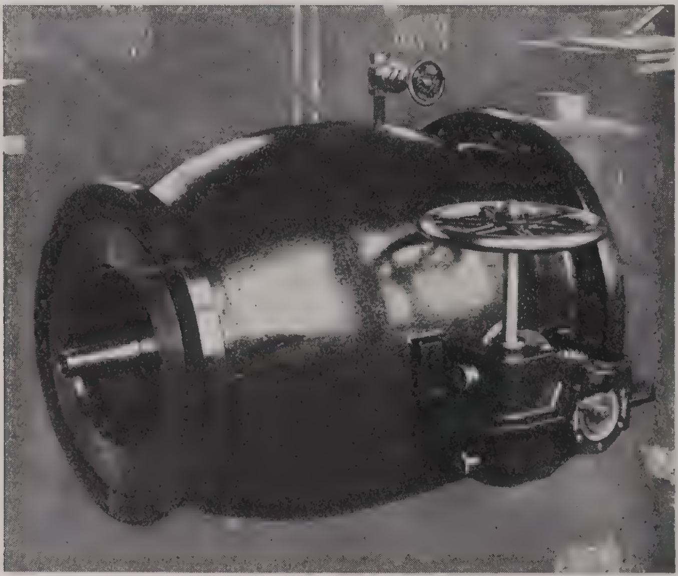
JOHNSON HYDRAULIC VALVES

Valves of the Johnson type have been constructed in sizes ranging from 5 inches to 21 feet Inlet diameter

These Valves are particularly adapted to the following uses:

HYDRAULIC TURBINE PENSTOCKS
PRESSURE PIPE LINES
HIGH PRESSURE FIRE SERVICE
AUTOMATIC REGULATION OF FLOW FROM RESERVOIRS
THROTTLING AND FREE DISCHARGE FROM HIGH TO LOW PRESSURE CITY WATER WORKS SYSTEMS



18-inch Johnson Valve built for the Southern Sierras Power Company and designed for free discharge into the atmosphere under a head of 400 feet

Special Johnson Valve Features

Simplicity of Operation
Tightness against Leakage when Closed
Strength of Design
Automatic Closure in Emergencies
Combination Stop and Check Valve Characteristic
Durability and Dependability

Write for Johnson Valve Bulletin No. 3

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Say you saw it advertised in the General Electric Review

THE Youngstown Sheet & Tube Co., Youngstown, Ohio, is typical of the many mills which have adopted our Data Sheet System and National Pyramid Brushes. On practically all of the machines in this great plant, National Pyramid Brushes are guarantors of electrical satisfaction and service.

Our Data Sheet System was originally used here. It proved its money and time-saving value from the first. But, being highly flexible, it was subsequently specially revised to fit Youngstown methods, and is now more highly prized than ever.

In mills, mines, on traction lines, interurban and interstate roads, in central stations—wherever electricity is generated, converted, or made to do work—National Pyramid Brushes afford marked economies.

Our sales engineers are at your service.

Where heavy starting torque or speed control is necessary, consider the advantages of commutator type motors.

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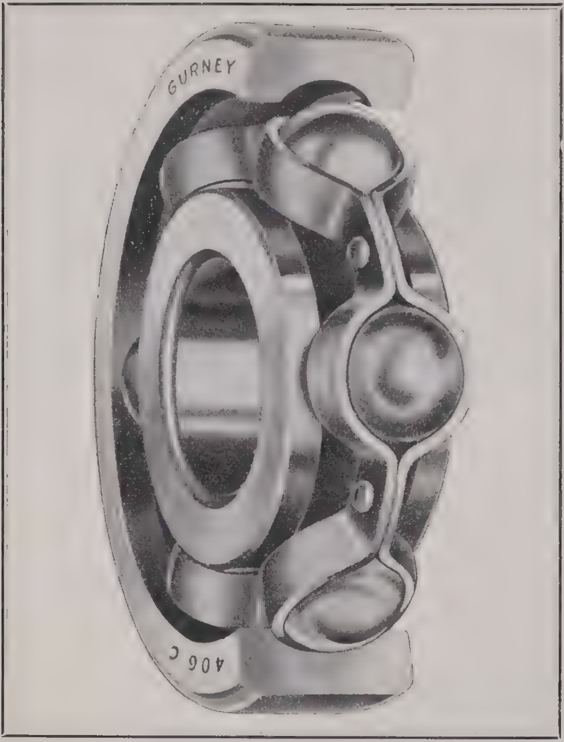

Deep Groove Type C

The deep, uninterrupted raceways, also high shoulders on both sides, of Gurney Type C Deep Groove ball bearings permit the bearings to be mounted with either side to the load as they safely withstand thrusts from either direction, in addition to a radial load. The rugged separator used greatly increases their thrust capacity.

We would welcome an opportunity to prove their superiority.

GURNEY TYPE C BALL BEARINGS

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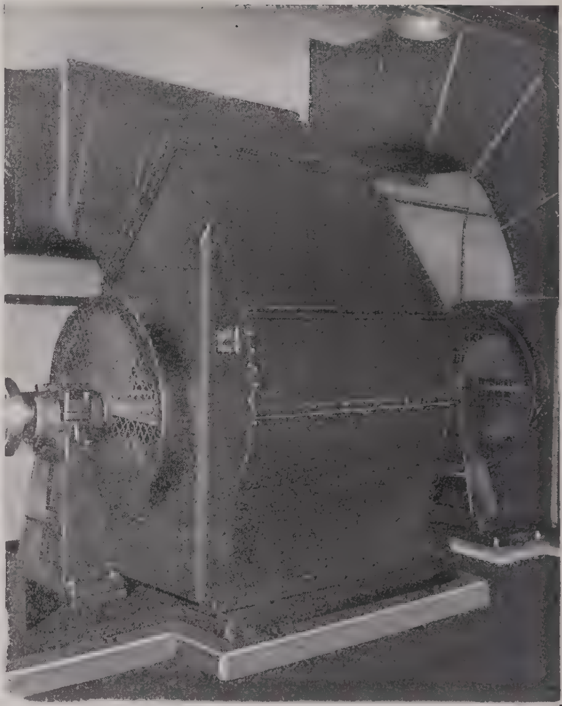

Buffalo Stoker Fan in an automobile factory

Industrial plants follow the power company

WHAT the huge central station finds satisfactory in the way of mechanical draft apparatus is usually the particular choice of those industrial plants that generate their own power.

Thus we find such companies as Buick, Cadillac, Fisher Body, Chevrolet, Ford and Studebaker, in the automotive industry; Dunlop, Goodyear, Goodrich, General Tire and Rubber, and Philadelphia Rubber Co., in the rubber industry; in the iron and steel manufacture some of the very largest, such as American Steel and Wire Co., American Rolling Mill Co., Bethlehem Steel Co., Central Steel Co., Cambria Steel Co., Carnegie Steel Co., Wierton Steel Co. and Youngstown Sheet and Tube Co.—all these industrial giants use Buffalo Stoker Fans.

Of course, there ARE real reasons for the popularity of these fans. A new catalog, No. 730-92, tells the whole story. Write for your copy now.

Buffalo Forge Company

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"Buffalo" *Mechanical Draft Apparatus*

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A COMPLETE ILLUSTRATED READY REFERENCE EDUCATOR

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Here is an up-to-date, quick Ready Reference. It gives complete instruction and inside information on every electrical subject. Every point clearly explained in plain language and diagrams that are easily understood. Handy to use. Easy to learn from. Subjects arranged in progressive manner for the student and with complete index which gives information instantly to professional workers. A time saver, money saver, and a helping hand for Engineers, Professional Electricians, Students and all interested in electrical work.

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Address..

Occupation..

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Oust a Cruel Fire Bug

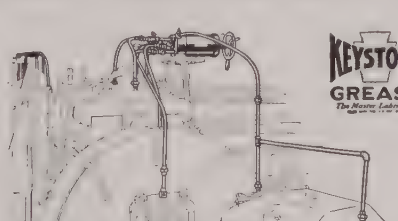
MANY a blaze, fire records show, is directly traceable to sparks igniting oil lying around on the floor in puddles. One plant had two very bad fires traceable to this cause. Two 200-h.p. units were destroyed by the fires.

They have ousted this hazard now by equipping their motor units with the Keystone Safety system of Keystone Grease Lubrication. They have eliminated all waste of lubricants besides. Cut costs.

Now with this Keystone System, "metal arms" reach out from the Keystone Safety Lubricator to the bearings all over the unit. Thru these feed lines Keystone Grease is forced, under high pressure, directly to the bearings from one central, safe place, without interrupting production.

Investigate!

KEYSTONE LUBRICATING CO.
Est. 1884
Philadelphia, Pa., **at 21st and Clearfield Streets**
Branches and warehouses in principal cities of the country

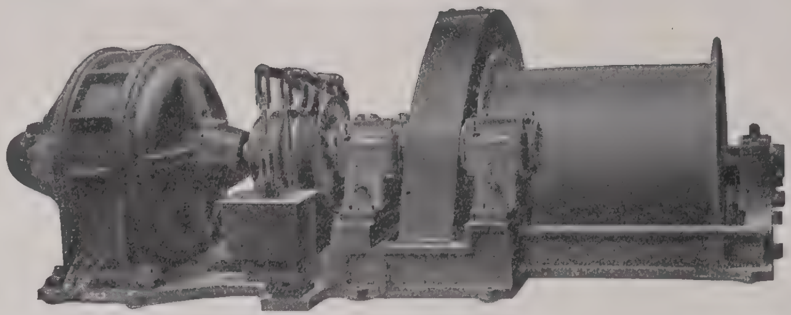


KEYSTONE GREASE
The Master Lubricant

Keystone Safety System of Keystone Grease Lubrication

Keystone Lubricating Co.,
Philadelphia, Pa.

Gentlemen: Please send me details of your Keystone Safety System of Keystone Grease Lubrication. My name, company name and address are written in the margin of the magazine below.



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Electric in All Sizes *Steam Up to 1000 H.P.*

Every quality, in design and construction, that tends to increase output and reduce cost of operation, is found in

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SMITH HYDRAULIC TURBINES

Accompanying view shows one of Four single-runner, vertical shaft, cast iron scroll-case Hydraulic Turbine Units now in successful operation in the Tugalo Plant of Georgia Railway & Power Co.

Each turbine develops 22,000 H.P. at 171.4 Rev. under 150 ft. head and is direct-connected to a 12,500 kw. General Electric Generator.

We have
The Experience,
The Resources, and
The Manufacturing Skill enabling us to render REAL SERVICE.

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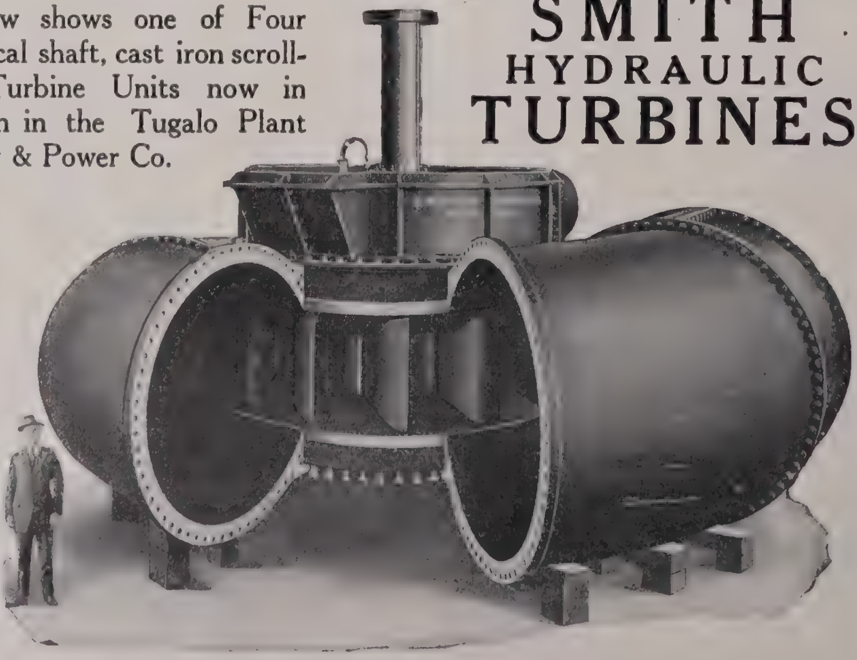

S. Morgan Smith Co., York, Pa.

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G-R EXPANSION JOINT

more than a fitting—an engineering achievement

GUARANTEED

[1] To compress one quarter inch axially when subject to a compressive force of 125 pounds per inch nominal diameter of pipe.

[2] To expand one quarter inch axially when subject to an expansive force of 150 pounds per inch nominal diameter of pipe.

[3] To distort laterally one eighth inch with a force of 125 pounds per inch nominal diameter of pipe.

Send for Form Sheet 178

THE GRISCOM-RUSSELL COMPANY

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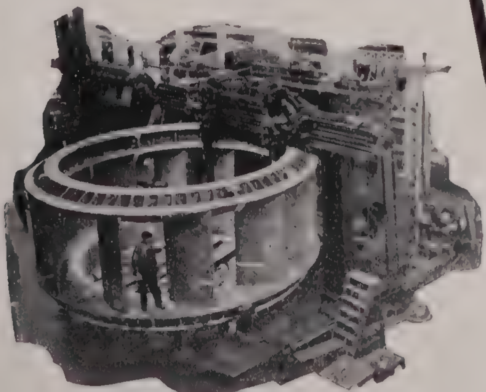

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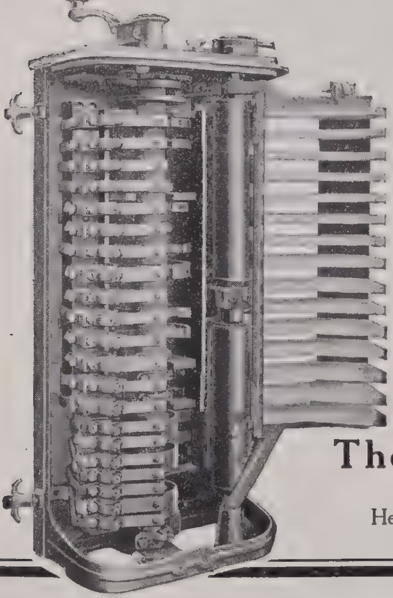

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GENERAL ELECTRIC REVIEW

A MONTHLY MAGAZINE FOR ENGINEERS

Manager, M. P. RICE Editor, JOHN R. HEWETT Associate Editor, E. C. SANDERS

Subscription Rates: United States and Mexico, $3.00 per year; Canada, $3.25 per year; Foreign, $3.50 per year; payable in advance. *Library and Student Rates:* United States and Mexico, $2.00 per year; Canada, $2.25 per year; Foreign, $2.50 per year; payable in advance.

Remit by post-office or express money order, bank check, or draft, made payable to the *General Electric Review*, Schenectady, N. Y.

Advertising forms close on the first day of the month preceding date of issue.

Entered as second-class matter, March 26, 1912, at the post-office at Schenectady, N. Y., under the Act of March, 1879.

Vol. XXVIII, No. 7

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JULY, 1925

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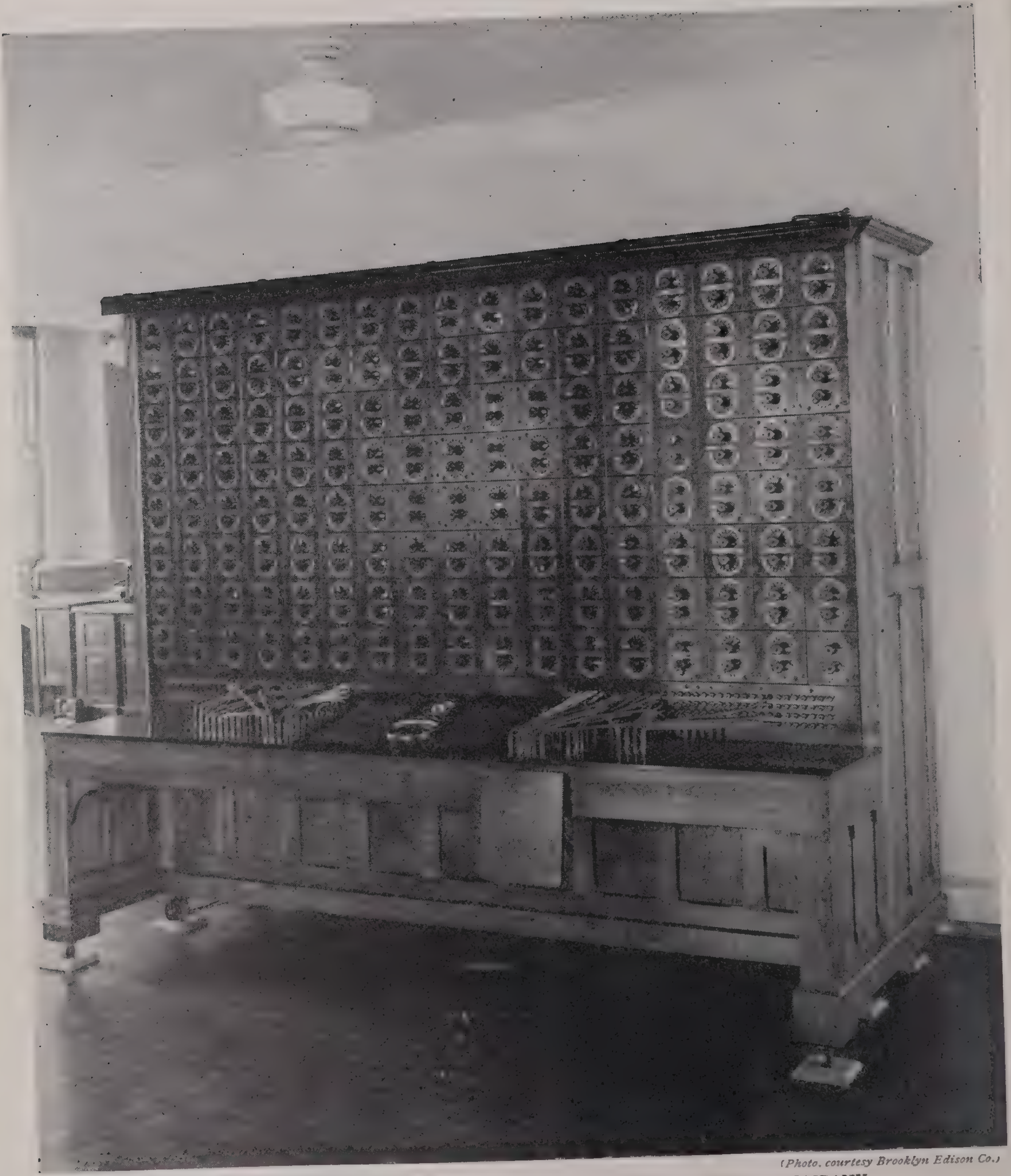


(Photo. courtesy Brooklyn Edison Co.)

SHORT-CIRCUIT CALCULATING TABLE OF THE BROOKLYN EDISON COMPANY

For checking up the existing system or laying out new lines, the company engineers set up the network on this table and from it are able to obtain complete short-circuit data for determining the size of oil circuit breakers and sectionalizing relays. The calculating table is of supplementary utility in connection with the determination of some of the single-phase short-circuit problems described on pp. 472 and 479.

GENERAL ELECTRIC REVIEW

THE DETERMINATION OF SINGLE-PHASE SHORT-CIRCUIT CURRENT ON THREE-PHASE SYSTEMS

With the growth of power systems and their interconnection, the study of the short-circuits to which these systems may be subjected assumes more and more importance. The calculation of symmetrical three-phase short-circuits has been reduced to a comparatively simple process by means of the short-circuit calculating table, an example of which is illustrated on the opposite page.

In the modern transmission system with its grounded neutral, the majority of short-circuits are from line to ground. If the arc under some circumstances is allowed to play for a sufficient time, it will spread and result in a line-to-line or three-phase short-circuit. The purpose of the best relay schemes is to open the circuit before the trouble spreads. In systems with isolated neutrals, the initial flashover does not cause a short-circuit but the resultant arcing ground may raise the ungrounded conductors to sufficient potential to arc over their insulators, thus causing a line-to-line or three-phase short-circuit.

Thus it is essential to be able to calculate line-to-line and line-to-neutral short-circuits on three-phase systems. This necessarily laborious task will be considerably simplified by following the directions given in the articles on pp. 472 and 479 of this issue.

In Mr. Lewis' article the principles of the well-known Kirchhoff's Laws are applied and some very simple relations worked out for the less complicated set-ups. For the more complicated set-ups, the method is still simple but much labor may be required in the mechanical process of extracting the solution from the equations. The method has the advantage that the physical relation of the various currents is throughout apparent from the preliminary diagram that is necessary before the equations are written.

Mr. Bekku employs a very ingenious principle not so well-known, namely, the Method of Symmetrical Co-ordinates, developed by Mr. C. L. Fortesque. The theory of Mr. Bekku's method is somewhat difficult to understand but the application is relatively simple. By this method and the calculating table in conjunction, we need no longer fear the most forbidding set-ups.

Included in Mr. Bekku's researches have been a study of the high-resistance grounded neutral, grounding the neutral through the arc suppressing reactor (Petersen Coil), the use of an overhead ground wire of low impedance, etc. Most of these valuable researches are published in the *Journal of the Japanese Institute of Electrical Engineers*, and in the publications of the Electrotechnical Laboratory, but unfortunately they are not generally available to the English reading public. For this reason we take great pleasure in publishing Mr. Bekku's present contribution, especially as the problem that he discusses is of timely interest to engineers in this country as well.

Relation of Engineering Education to Industry

By Francis C. Pratt
Vice President in Charge of Engineering and Manufacturing
General Electric Company

Mr. Pratt has long taken active part in movements to improve the education of those who choose to follow the engineering profession, and his latest expressions of thought on this subject are contained in the following article which was delivered by him on June 19, 1925, as a paper before the Annual Convention of the Society for Promotion of Engineering Education at Union College, Schenectady, N. Y. In it he shows what is being done by one large manufacturer to develop the engineers of tomorrow to their maximum state of usefulness. —Editor.

While journeying in French North Africa during the late Autumn of last year I saw many examples of craftsmanship and crude industry, all the way from Marrakech in the Southwest to Tunis in the Northeast. One of the things which particularly impressed me was the rudimentary lathe used for turning wood spindles and, in some cases, small metal shafts, operated by an old and bent man or by a boy.

The implement consisted of head and tail stocks, each with fixed spindles, the head stock fastened to the wooden base and the tail stock sliding along the base, a simple tool rest and a wooden bow strung with a loose cord which was twisted around the end of the piece to be turned. The operator would take a piece of wood, adjust one end to the head stock center, bring up the tail stock center to support the other end, and with his left foot bring sufficient pressure to bear upon the tail stock to hold the work in place. He would next take the cutting tool, consisting of a comparatively long steel bar, place it on the tool rest and with the toes of his right foot guide the forward end, while with one hand he steadied the rear end of the tool. With the other hand he rapidly moved the bow back and forth supplying the motive power.

With this crude device wooden spindles were turned out with somewhat surprising rapidity, but the older men gave evidence that long years of work under these cramped conditions resulted in permanent deformity.

It will be noted that in this combination of operator and his equipment we have a self-contained power plant and a wood or metal working tool for the operation of which there is no demand for an understanding of the complex details of turbine generators, secondary apparatus, transmission lines, motors and control, which constitute the modern power system. The amount of power used is of course very small; and, as it is recognized in general that the productivity of a country bears a direct relation to the power consumption per capita, the output of merchandise in these backward countries is very small compared with our accepted standards.

It is apparent that in such a crude industry there is little demand for engineering education.

A familiar treatise on this branch of learning is "A Study of Engineering Education," by Dr. Charles Riborg Mann, prepared for the Joint Committee on Engineering Education of the National Engineering Societies and issued in the year 1918 by the Carnegie Foundation for the Advancement of Teaching. In this study Dr. Mann points out that engineering schools are obviously a result of the needs of industrial production.

In the very interesting chapter on the "Development of Engineering Schools in the United States," he refers to the Report of the Committee on Agriculture presented by Jesse Buel to the New York State legislature on March 29, 1823, as perhaps the most complete and expressive of an enormous number of the current memorials, petitions, and committee reports to the various state legislatures, calling attention to the fact that the exhaustion of the soil because of unscientific methods of agriculture was already driving the population to seek new land in the West, and crying for instruction in better methods of farming and better means of transportation to the West. Dr. Mann points out that the following year Mr. van Rensselaer established at Troy the pioneer school of its kind in the United States, the Rensselaer Polytechnic Institute, and that in 1829 the curriculum was revised, a course in civil engineering added, and that for a quarter of a century this school divided with the West Point Military Academy the honor of supplying men with scientific training to meet the country's need for engineers.

The vast growth which has taken place in engineering education in this country since those early days is appreciated by all.

In speaking further upon this subject, I will address myself more particularly to the requirements for engineering education in connection with the electrical industry with which I am immediately associated.

This industry is one of the younger of our modern group of great industries, whose infancy dates back scarcely more than forty years. In its early days there were but few available men who could be regarded as trained electrical engineers, and at that time our colleges offered little or nothing in the way of comprehensive courses in electrical engineering. There were a comparatively few outstanding men engaged in the industry who possessed profound knowledge of the fundamental laws of the physical and mathematical sciences, and these men became great teachers to those fortunate youths coming within the sphere of their immediate personal influence. Under these conditions many of these youths, who had not had the advantages of a college education, acquired through native intelligence and perseverance a firm grasp of both theory and practice and have, as individuals, contributed much to the development of the industry. There were also attracted to these new enterprises many graduates of mechanical and civil engineering courses of our colleges, and many of these men have likewise made great contributions to the development of the industry.

In the early days of the electrical industry much of the testing of electrical apparatus was done by workmen having only the most rudimentary knowledge of electrical theory; yet it soon became apparent that in order to meet the demands of a rapidly growing industry, the testing of electrical apparatus prior to shipment offered a singularly favorable facility for the acquisition of practical knowledge by young men who had already studied electrical theory in college. Thus the so-called "Testing Course" became an important and integral part of practically all large electrical manufacturing companies.

The start thus made has never ceased to evolve and expand,to the end that large manufacturers today maintain a variety of carefully planned and conducted courses to give advanced teaching and experience to college graduates for the purpose of specially preparing them for the particular branches of the enterprise to which they are drawn by natural qualifications and inclination.

Voicing my own opinion on this subject, we are not looking to the colleges and technical schools to turn out finished engineers, but we do look to them for a steadily increasing supply of young men who have been thoroughly trained in the fundamental theories of the mathematical and physical sciences, and to the fullest practicable extent in economics and in what are commonly called the cultural studies. We believe that with this ground-work thoroughly prepared, the large industries are in a particularly favorable position to offer exceptional opportunities to young men for gaining practical knowledge and experience along special lines.

In this connection, I wish to make it quite clear that in the foregoing remarks I am not including those exceptional students who by natural qualifications and inclinations are prepared to pursue post graduate studies in theoretical work in any branch of science or engineering which contributes to the industry; in fact, in a previous paper presented before this Society, I pointed to the significant fact that in the Organization with which I am in daily contact a noticeable number of our most accomplished theoretical engineers and research laboratorians have either pursued post graduate studies at European Universities or else have had all of their scholastic training abroad, and that this might suggest an opportunity for American educational institutions which is not fully met at the present time.

In order to present a more definite measure of the importance placed upon engineering education by the great industrial organization with which I have the honor to be associated, I wish to point out that in a normal year we take in considerably over four hundred graduates of our colleges and technical schools. A great majority of these young men are either electrical or mechanical engineering graduates and enter the Test Courses established at each of our principal Works; there are, however, limited numbers specializing in Chemistry and Physics, who enter directly into our laboratory work.

We recognize a responsibility for supplying the essential training, afforded by the Test Course, to the largest practicable number of young engineers, not only for our own requirements but for those of the electrical industry at large.

Our experience over a term of years indicates that approximately 50 per cent of these young men enter into permanent employment with our own Company, while the remainder either enter the employ of our customers or go into other vocations, following their own initiative.

While practically all of the engineering graduates spend the first year in the Test Course, yet before the end of that period the selective process begins and continuation courses are projected leading up to engineering, manufacturing, commercial, and administrative work.

A special group of about ten mechanical engineering graduates is selected each year to enter the Factory Training Course. In order to give them first-hand experience with manufacturing processes, these students are given progressive assignments in the more important branches of factory work. Paralleling this, they are also given classroom work in Economics, Factory Accounting, and Organization. Graduates of this Course will undoubtedly grow to responsible positions in the Manufacturing Organization.

In order to emphasize further the importance which industry places upon highly trained engineers, well versed in theory and practice, and possessing such knowledge of material values and of men as to render their work effective, I wish to call attention to one of our recent experiences:

A little over two years ago a conference of a small group of our leading engineers was called to consider what was regarded as the existing and future demand for a limited number of very highly trained engineers, having the best possible knowledge and experience in applying the theory of mathematical and physical sciences to engineering practices, in order, not only that they may be competent to cope successfully with difficult engineering problems connected with our current business, but also that they may be available for the solution of problems in new and untried fields, such as arise from time to time. The objective was not so much the development of highly trained specialists as the training of a limited number of good all-round engineers. It was recognized that the course would be a very difficult one, extending over a three-year period, comprising work in the Engineering Department, the factory, and class room. The opinion was expressed that we would probably need not more than six such carefully trained men a year, and that quite irrespective of the cost of the undertaking we would feel satisfied if one really exceptional man with marked creative ability developed every two years. A census was then taken of all of the engineering departments of the Company, and we were somewhat surprised to receive a report that we could utilize about ten such men per year if they were available. We still feel that, after the demand of the first few years has been satisfied, our original estimate of perhaps six or seven per year will fill the requirements; moreover, experience rather indicates that not more than this number, of the calibre we have in mind, will be available. Doubting our ability to select the best men from preliminary examinations, it was decided that thirty men should be admitted to the first year's course which included work in the Testing Department and that by the end of the year twenty would be eliminated, leaving a remainder of ten to continue the advanced work over the two succeeding years. A serious question was raised as to whether a sufficient number of young men would be interested to enter into so exacting an undertaking, but when this Advanced Course in Engineering was announced a year ago last September we were tremendously gratified to have seventy-one applicants eagerly seeking admittance, and the following year the number of applicants increased to one hundred and one. When we consider that these men formed a part of a group of approximately four hundred college graduates, who in turn had been selected with the greatest care, it is apparent that a very high degree of selectivity has been exercised in picking the candidates for this course. The results thus far have fulfilled our most sanguine expectations; and at this time, while a new group of thirty students has entered into the first year of the course, the ten men selected at the end of last year are continuing their work in the second year with accomplishments that are highly gratifying to all.

We are confident that out of this group of young men will come individuals who will exert great influence upon the future of our industry and upon the engineering profession.

Also, during this current year we are taking more than fifty college graduates into a Business Training Course conducted under the supervision of our General Office Accounting Department. This course plans to give thorough instructions in Advanced Accountancy, Economics, Industrial History, Theory of Management, and Commercial Law, particularly as applied to the business of our Company.

I wish also to point out, with relation to our educational program, that the student engineers of the Schenectady Works for several years past have been offered the opportunity of obtaining their Master's degree from Union College by attending classes one-half day each week, normally completing the course in two years.

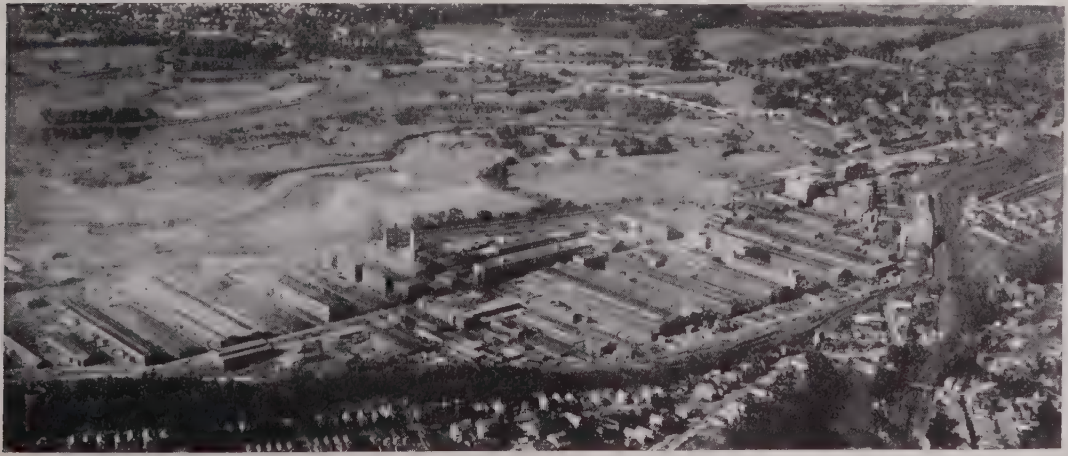
A Co-operative Course for Company employees has just been initiated between our Lynn Works and the Massachusetts Institute of Technology leading to the Master's degree.

Arrangements have been made whereby a group of College Professors enter into the nominal employ of the Company for a period of five weeks during the Summer months. Our experience indicates that this is helpful in establishing and maintaining close contact between the work of the engineering colleges and of our Engineering Department, and that the interchange of ideas reacts beneficially on the teaching given in the colleges and on our own engineering practices.

In closing I do not think that I can do better than quote a few extracts from an article entitled "Some Reflections on Democracy and Education," by President James Rowland Angell, of Yale University, which appeared in the April, 1925, issue of the quarterly *Yale Review*. President Angell says:

> "Probably no test will, in the long run, be so decisive for democracy as its ability and willingness to exercise wisdom in the selection of its leaders. Putting the same issue from a different angle, it may be said that democracy will be critically tested by the willingness of those who have been best trained and who have enjoyed the fullest privilege to make the necessary sacrifice of comfort and convenience to serve the state * * * * The leadership for which democracy must train is not solely that of a political character, important as that may be. It must also extend to every aspect of the economic and cultural life of the people. In the measure in which real talent is overlooked, or snubbed, or misplaced, the welfare of the community is wounded and no conception of education in a democracy could be accepted as valid and adequate which did not provide for the detection of specific ability, its training and its location at strategic points in the structure of society. If such a demand be thought to imply autocratic interference with individual initiative or bureaucratic domination of the individual career, the purport of the remark has been misunderstood.
>
> "For my own part, I believe that, so far from having overdone the possibilities of education, our generation has only begun to sound them. I look to see the present forms substantially changed, but the underlying spirit, which is that of the unrestricted offer of opportunity and the search for the fittest to fill each post in the social order * * * * this I confidently expect to see gain in power and intelligence of execution from this day on."

What President Angell has so eloquently expressed in these words, as the educational needs of democracy at large, is only to a lesser degree the needs of our industry today and in the future.



Airplane View of the Schenectady Works, General Electric Company

Calculation of Short-circuit Ground Currents on Three-phase Power Networks, Using the Method of Symmetrical Co-ordinates

By Sadatoshi Bekku

Electrotechnical Laboratory, Department of Communications,
Tokyo, Japan

In both the design and maintenance of modern power networks it is necessary to determine the theoretical values of all possible short-circuit currents in order that the relays may be installed and adjusted to provide the best sectionalizing action in time of trouble. So long as the short-circuit is symmetrical with respect to the three phases, the currents in the network will be balanced, and their determination on the calculating table will be simple. But this condition is, unfortunately, rare. In the more common case, when only one phase is short-circuited, or when a single conductor is grounded, the condition that follows is one of extreme unbalance. To determine the currents in this case has always been a matter of long calculation. Mr. Bekku's article presents a method of reducing the unbalanced currents to three sets of components readily solvable on the calculating table.—Editor.

Introduction

Recent developments in power systems have led to the direct grounding of the neutral to facilitate the action of protective relays and to lessen the voltage stress on high-tension transformers. When an accidental ground occurs on one line of the power system, a heavy short-circuit current results.

The direct grounding of the power system neutral is the recent trend of practice in the United States and this has proved to be very successful in assuring satisfactory relay operation.

The increasing difficulty in securing right-of-way privileges forces the construction of both power and communication lines along the common highway and thus promotes inductive interference. In Japan, owing to the geographical conditions, it has been practically impossible to separate the power lines from the communication lines sufficiently to overcome the inductive interference due to the direct grounding of power system neutrals. For this reason, direct grounding of the neutral has not yet been generally adopted in Japan. However, the growing power demand gives rise to the contemplation of longer transmission lines of higher voltage and the problem of the grounded neutral has become more serious in connection with the initial cost and the satisfactory operation of the system.

In the present article a method of calculating the ground current, taking into account the characteristic phase balancing action of the synchronous alternators, is developed. The calculating table, which is generally used to calculate the three-phase short-circuit current in a complicated power network, can also be used with a slight modification for the present purpose.

Method of Symmetrical Co-ordinates

Electromagnetic inductive interference depends upon the inducing current in the power circuit and on the mutual impedance between power and communication lines. We have not yet sufficient data on mutual impedance and we have therefore availed ourselves in Japan of every chance to get a wider knowledge of it.

The inducing current can be calculated with sufficient accuracy and easily checked by actual test. An accurate method of calculation for a simple three-phase line of any length, however long, with uniformly distributed inductance and capacitance, was worked out in the author's previous paper.⁽¹⁾ When the network becomes complicated, however, the determination of the short-circuit currents is a troublesome task. The calculation is greatly facilitated by neglecting the line capacity.

A paper on this subject was published by Mr. R. A. Shetzline,⁽²⁾ but the mutual impedance necessarily introduced in his method makes the use of the calculating table very difficult and furthermore the phase balancing action of ordinary synchronous alternators seems to have been ignored in his paper.

In the present article, the rigorous method used to calculate the short-circuit current as well as the current in each phase due to

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(1) S. Bekku, "Researches of the Electrotechnical Laboratory, Tokyo, Japan." No. 129.

(2) *Journal A.I.E.E.*, November, 1924.

the grounding of one line, considering the phase balancing action of ordinary alternators, is developed in terms of the Method of Symmetrical Co-ordinates proposed by Mr. C. L. Fortescue.(3) Those who are not familiar with this method are recommended to refer to the original paper and the discussion of it offered by Dr. J. Slepian.

Mathematical Analysis

Let I_{a0}, I_{a1}, and I_{a2} be the zero, positive, and negative phase sequence components respectively of I_a, I_b and I_c (Fig. 1).(4) Then the phase sequence components of current flowing into the symmetrical load are obtained as follows:

Zero phase sequence component $= I_{a0} - I_e$
Positive sequence component $= I_{a1} - I_e$
Negative sequence component $= I_{a2} - I_e$

$$\text{where } a = \epsilon^{j\frac{2\pi}{3}} = -\tfrac{1}{2} + j\frac{\sqrt{3}}{2}$$

Consider a symmetrical three-phase power source with grounded neutral and let the induced electromotive forces in the three phases be E_a, E_b, E_c. Then since this power source is symmetrical, E_a, E_b, and E_c constitute a symmetrical three-phase e.m.f., e.g., $E_b = a^2 E_a$ and $E_c = aE_a$. If currents I_{a0}, I_{a0}, I_{a0} flow in phases a, b and c, respectively, then the phase voltage drops will be $Z_0 I_{a0}$, $Z_0 I_{a0}$ and $Z_0 I_{a0}$.

If there are symmetrical three-phase currents, e.g., I_{a1} in phase a, $a^2 I_{a1}$ in phase b and aI_{a1} in phase c, then the voltage drop will be $Z_1 I_{a1}$ in phase a, $a^2 Z_1 I_{a1}$ in phase b and $aZ_1 I_{a1}$ in phase c.

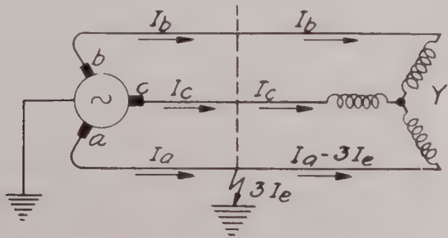

Fig. 1. Loaded Generator with One Phase Grounded

If the symmetrical three-phase currents are of opposite phase sequence, e.g., I_{a2} in phase a, aI_{a2} in phase b and $a^2 I_{a2}$ in phase c, then the voltage drop will be $Z_2 I_{a2}$ in phase a, $aZ_2 I_{a2}$ in phase b and $a^2 Z_2 I_{a2}$ in phase c.

If there is a current
$I_{a0} + I_{a1} + I_{a2} = I_a$ in phase a,
$I_{a0} + a^2 I_{a1} + aI_{a2} = I_b$ in phase b and
$I_{a0} + aI_{a1} + a^2 I_{a2} = I_c$ in phase c,
then the voltage drop in each phase will be
$Z_0 I_{a0} + Z_1 I_{a1} + Z_2 I_{a2}$ in phase a,
$Z_0 I_{a0} + a^2 Z_1 I_{a1} + aZ_2 I_{a2}$ in phase b.
$Z_0 I_{a0} + aZ_1 I_{a1} + a^2 Z_2 I_{a2}$ in phase c.

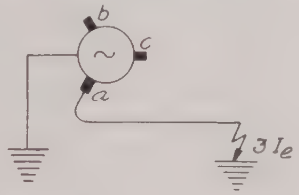

Fig. 2. Ground on Open-circuited Generator

If V_a, V_b, V_c are the potentials at the terminals then we have

$$\begin{aligned} V_a &= E_a - (Z_0 I_{a0} + Z_1 I_{a1} + Z_2 I_{a2}) \\ V_b &= E_b - (Z_0 I_{a0} + a^2 Z_1 I_{a1} + aZ_2 I_{a2}) \\ V_c &= E_c - (Z_0 I_{a0} + aZ_1 I_{a1} + a^2 Z_2 I_{a2}) \end{aligned}$$

Combining these expressions to form the symmetrical components as follows:

$$\begin{aligned} V_{a0} &= 1/3\ (V_a + V_b + V_c), \\ V_{a1} &= 1/3\ (V_a + aV_b + a^2 V_c), \\ \text{and } V_{a2} &= 1/3\ (V_a + a^2 V_b + aV_c), \end{aligned}$$

we have the following simple relations:

$$\left.\begin{aligned} V_{a0} &= -Z_0 I_{a0} \\ V_{a1} &= E_a - Z_1 I_{a1} \\ V_{a2} &= -Z_2 I_{a2} \\ V_a &= V_{a0} + V_{a1} + V_{a2} = 0 \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} I_{a0} - I_e &= 0 \\ I_{a1} - I_e &= Y\ V_{a1} \\ I_{a2} - I_e &= Y\ V_{a2} \end{aligned}\right\} \quad (2)$$

where E_a is the nominal induced electromotive force of phase a, line to neutral, and Y is the admittance of the symmetrical three-phase load. Solving (1) and (2), we have,

$$\left.\begin{aligned} I_{a0} = I_e &= \frac{(1 + Z_2\,Y)\,E_a}{\Delta} \\ \text{where} \quad & \\ \Delta &= (1 + Z_1\,Y)\,(1 + Z_2\,Y)\,Z_0 \\ &\quad + Z_1\,(1 + Z_2\,Y) + Z_2\,(1 + Z_1\,Y) \end{aligned}\right\} \quad (3)$$

If there is no three-phase load or if the line a is simply short-circuited to ground as shown in Fig. 2, we have by putting $Y = 0$ in (3):

$$I_{a0} = I_e = \frac{E_a}{Z_0 + Z_1 + Z_2} \quad (4)$$

Two Power Sources

Let two symmetrical three-phase alternators be connected in parallel and let the line a be grounded as shown in Fig. 3. The impedances and the currents are designated by suffixes in the following relations:

---

(3) *Trans. A.I.E.E.*, 1918, Vol. 37, Part 2, p. 1027.

(4) $I_{a0} = \frac{1}{3}\,(I_a + I_b + I_c)$.
$I_{a1} = \frac{1}{3}\,(I_a + aI_b + a^2 I_c)$.
$I_{a2} = \frac{1}{3}\,(I_a + a^2 I_b + aI_c)$.

$$\left.\begin{aligned} I_{a0}+I_{\alpha 0}&=I_e\\ I_{a1}+I_{\alpha 1}&=I_e\\ I_{a2}+I_{\alpha 2}&=I_e \end{aligned}\right\} \tag{5}$$

$$\left.\begin{aligned} V_{a0}&=-Z_{a0}\,I_{a0}=-Z_{\alpha 0}\,I_{\alpha 0}\\ V_{a1}&=E_a-Z_{a1}\,I_{a1}=E_\alpha-Z_{\alpha 1}\,I_{\alpha 1}\\ V_{a2}&=-Z_{a2}\,I_{a2}=-Z_{\alpha 2}\,I_{\alpha 2}\\ V_a&=V_{a0}+V_{a1}+V_{a2}=0 \end{aligned}\right\} \tag{6}$$

If we solve (5) and (6) we can get the magnitude of I_e, I_{a0} and $I_{\alpha 0}$, where $3I_{a0}$ and $3I_{\alpha 0}$ are the components producing the electromagnetic inductive interference on the neighboring communication line.

We have from (5) and (6):

$$\left.\begin{aligned} I_{a0}&=Z_{\alpha 0}\,(Z_{a2}+Z_{\alpha 2})\,(Z_{\alpha 1}\,E_a+Z_{a1}\,E_\alpha)/\Delta\\ I_{\alpha 0}&=Z_{a0}\,(Z_{a2}+Z_{\alpha 2})\,(Z_{\alpha 1}\,E_a+Z_{a1}\,E_\alpha)/\Delta\\ \Delta\ &=Z_{a0}\,Z_{\alpha 0}\,(Z_{a1}+Z_{\alpha 1})\,(Z_{a2}+Z_{\alpha 2})\\ &\quad+Z_{a1}\,Z_{\alpha 1}\,(Z_{a0}+Z_{\alpha 0})\,(Z_{a2}+Z_{\alpha 2})\\ &\quad+Z_{a2}\,Z_{\alpha 2}\,(Z_{a0}+Z_{\alpha 0})\,(Z_{a1}+Z_{\alpha 1}) \end{aligned}\right\} \tag{7}$$

Effect of Line Impedance

If the line connecting two power sources is sufficiently long, it is evident that the line impedance must be taken into account to calculate the magnitude of the short-circuit current in case of a one-line ground.

The impedance of the three-phase line, symmetrically disposed for the balanced three-phase current, is well known and can be obtained from the resistance of the conductor, size of conductor, spacing between conductors and the frequency, as follows:

$$Z_l=\rho+jw\,(2\log_e\frac{d}{r}+\tfrac{1}{2})\times 10^{-4} \tag{8}$$

where

Z_l = impedance in ohms per km.
ρ = resistance in ohms per km.
r = radius of conductor in cm.
d = spacing between the conductors in cm.
$w=2\pi f$ where f is the frequency.

The impedance obtained in this equation is the positive and at the same time negative phase sequence impedance per kilometer length of the line. The zero phase sequence impedance of the line is three times the impedance of three conductors in parallel with ground return. The effective resistance and reactance depends not only on the geometrical configuration of the conductor, but also on the geological condition of the earth.

Extensive experiments were carried out in Japan to obtain the effective impedance of the aerial line with ground return in connection with inductive interference investigations. According to Mr. K. Kasai, of the Electrotechnical Laboratory at Tokyo, the effective inductance per km. length can be expressed by the following empirical formula for lines of various sizes; (for lines with a working voltage ranging from 110 to 154 kv., and with various distances between the two earthing points ranging from about 30 up to 400 km., the frequency at which the impedance was measured being 50 or 60 cycles per second):

$$L=2.25+0.0014D \tag{9}$$ (5)

with L in millihenrys per km., and D the distance between the two earthing points in km.

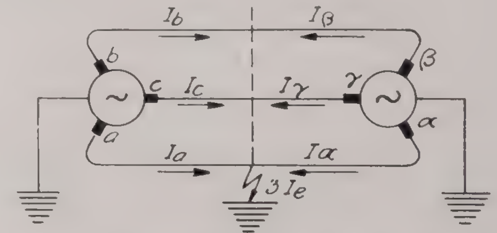

Fig. 3. Parallel Generators with One Phase Grounded

The phase angle of the effective impedance of the aerial line with earth return was found in every case to be about 70 deg. The effective inductance for the case when there are many earthing points is not yet known, but since the effect of D on L is not very great we can safely take a certain appropriate magnitude of L for individual cases.

Assume a three-phase aerial line symmetrically disposed with respect to ground and let the radius and spacing be r and d respectively. The effective self inductance of each line with ground return will be L and their mutual inductance, M. For the balanced three-phase current condition, the effective self inductance for each conductor is

$$0.2\log_e\frac{d}{r}+0.05\text{ mh/km}$$

On the other hand, the effective self inductance is $L-M$; therefore

$$0.2\log_e\frac{d}{r}+0.05=L-M$$

From this relation we can get the mutual inductance M.

Now the zero phase sequence reactance of the three-phase line is $j\omega\,(L+2M)$ per unit length, and taking $L=2.50$ mh/km for the average transmission system, we obtain the zero and positive phase sequence reactances of the aerial line as given in Table I. The reactances are to be used only for the actual calculation of the earth current with the aid of the calculating table.

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(5) This gives a relation of $X_0=0.0227f\left(1+\frac{l}{1000}\right)$ ohms per mile, where f = frequency and l = length in miles.

TABLE I

APPROXIMATE REACTANCE OF AERIAL LINE, FOR 60 CYCLES, IN OHMS PER MILE

d/r	Z_l'	Z_l
100	3.43	0.559
150	3.33	0.608
200	3.27	0.643
250	3.21	0.670
300	3.16	0.691
350	3.13	0.712
400	3.09	0.726
450	3.06	0.740
500	3.04	0.754

(Ground wire of low impedance not taken into account.)

Let the zero and positive phase sequence impedance per unit length be Z_l' and Z_l respectively. Then the current in the case shown in Fig. 4 is obtained by changing the Z's in equation (7) as shown in the following:

$$\begin{array}{ll} \text{In place of} & \text{put in equation (7)} \\ Z_{a0} & Z_{a0}+Z_l'\,x \\ Z_{a1} & Z_{a1}+Z_l\,x \\ Z_{a2} & Z_{a2}+Z_l\,x \\ Z_{\alpha 0} & Z_{\alpha 0}+Z_l'\,y \\ Z_{\alpha 1} & Z_{\alpha 1}+Z_l\,y \\ Z_{\alpha 2} & Z_{\alpha 2}+Z_l\,y \end{array} \Bigg\} \quad (10)$$

Use of the Calculating Table

For the calculation of short-circuit currents in the case of a three-phase short-circuit, the convenience of the calculating table developed by the General Electric Co.(6) is generally acknowledged.

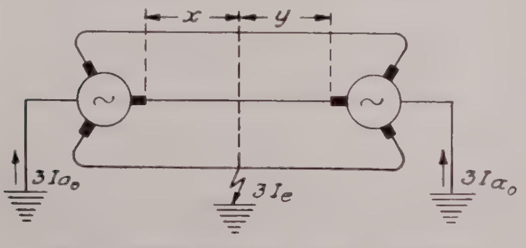

Fig. 4. Diagram for Ground Current Calculation

The calculating table can be utilized with some modifications for the present purpose of calculating the ground current in the case of a one-line ground in the grounded Y network.

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(6) W. W. Lewis—"A New Short-circuit Calculating Table." GENERAL ELECTRIC REVIEW, August, 1920, p. 669.

Suppose all of the impedances in equation (6) are purely reactive and E_a and E_α exactly equal; then we can easily see that

$$\text{(I)}\quad \left\{\begin{array}{l} I_{a0} \text{ and } I_{\alpha 0} \\ I_{a1} \text{ and } I_{\alpha 1} \\ I_{a2} \text{ and } I_{\alpha 2} \end{array}\right\} \text{ are in the same phase.}$$

From (5) we see that

$$\text{(II)}\quad \left\{\begin{array}{l} I_{a1} \text{ and } I_{a0} \\ I_{a2} \text{ and } I_{a0} \end{array}\right\} \text{ are in phase.}$$

From these we see that

$$\text{(III)}\quad \left\{\begin{array}{r} -V_{a1} \text{ and } V_{a0} \\ V_{a2} \text{ and } V_{a0} \end{array}\right\} \text{ are in phase.}$$

Therefore, $V_{a0}+V_{a2}$ is in phase with $-V_{a1}$.

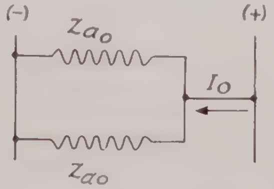


Fig. 5. Equivalent Diagram for First Setting

First Setting

The first step is to set up the circuit in zero phase sequence impedance as shown in Fig. 5.

Then the generator current I_0 obtained from the calculating table corresponds to I_e for the magnitude 100 per cent of $-V_{a0}$. It is evident that I_e is proportional to V_{a0}.

At the same time measure the current in every branch.

Second Setting

Next set up the circuit in positive phase sequence impedance as shown in Fig. 6, exactly in the same manner as in calculating the three-phase short-circuit current.

The total current I_1 to earth corresponds to I_e for $V_{a1}=0$. If V_{a1} is not equal to zero, an electromotive force corresponding to V_{a1} must be placed between the generator terminal and negative bus, instead of direct earthing. The current to the negative bus decreases in magnitude proportionally to V_{a1}.

Third Setting

Next set up the circuit in negative phase sequence impedance as shown in Fig. 7, similar to the first setting.

The generator current I_2 corresponds to I_e for the magnitude 100 per cent of $-V_{a2}$. It is evident that I_e is proportional to V_{a2}. From the above three settings we have the relation between I_0 and $-V_{a0}$, I_1 and V_{a1}, I_2 and $-V_{a2}$ as shown in Fig. 8.

In Fig. 8 draw a straight line *abc* horizontally from any point *a* on the vertical axis OY cutting OI_0 and OI_2 at *b* and *c*. Set *ad* equal to $ab+ac$. Draw a straight line OP joining O and *d*, cutting XI_1 at P.

Let P correspond to I_e in current value, then I_e is the solution satisfying equations (5) and (6), because for this value of I_e we satisfy the condition

$$V_{a1}=-(V_{a0}+V_{a2})$$

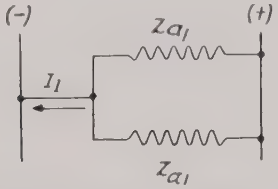


Fig. 6. Equivalent Diagram for Second Setting

The current obtained from each setting multiplied by I_e/I_0, I_e/I_1, I_e/I_2 respectively, gives the actual symmetrical component in the case of a one-line ground. The magnitude of I_e can be obtained by calculation as follows:

$$I_e=\frac{I_0\,I_1\,I_2}{I_0I_2+I_1I_2+I_0I_1} \qquad (11)$$

The actual current in the conductor of each phase can be easily obtained by means of the general vectorial relation

$$\left.\begin{aligned} I_a&=I_{a0}+I_{a1}+I_{a2}\\ I_b&=I_{a0}+a^2I_{a1}+aI_{a2}\\ I_c&=I_{a0}+aI_{a1}+a^2I_{a2}\end{aligned}\right\} \qquad (12)$$

I_a is obtained simply by adding the magnitudes of I_{a0}, I_{a1} and I_{a2}.

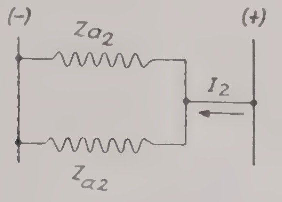


Fig. 7. Equivalent Diagram for Third Setting

This principle can be applied to any complicated network and the calculating table can be utilized, provided all alternators have identical nominal induced electromotive forces and all impedances are purely reactive, which case is also assumed in calculating the three-phase short-circuit.

First set up the circuit with zero phase sequence impedance and with a single generator of zero impedance placed at the point where the ground is supposed to occur. Obtain the generator current I_0 as well as the current in every branch.

For the next step set up the circuit with positive phase sequence impedance, in exactly the same manner as to obtain the three-phase short-circuit current. The short-circuit is made at the point where the ground is supposed to occur. Obtain the total current I_1. The current in every branch is necessary only when the actual current in each phase is required or when the duty of the oil circuit breaker is being considered.

Then set up the circuit with negative phase sequence impedance and with a single generator of zero impedance placed at a point where the ground is supposed to occur. Obtain the generator current I_2.

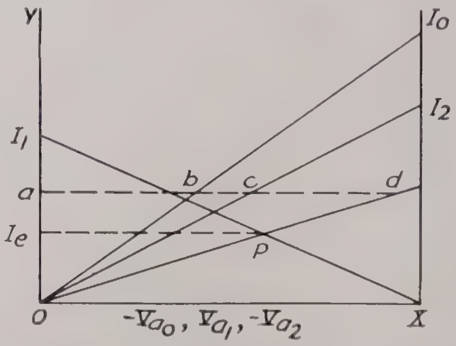


Fig. 8. Voltage and Current Vector Relations

Then we have the total current flowing to earth from the grounded point given by

$$3I_e=\frac{3I_0I_1I_2}{I_0I_1+I_0I_2+I_1I_2} \qquad (13)$$

The zero phase sequence component in any branch of the complicated network is obtained by multiplying the current obtained from the first setting of the calculating table by a factor, I_e/I_0. Likewise, the positive and negative phase sequence components in any branch are obtained by multiplying the table values by I_e/I_1 and I_e/I_2 respectively.

Example 1

Single power source; one line short-circuited to neutral (Fig. 9).

Let the sustained impedance values be as follows:

$Z_0=10$ per cent.
$Z_1=90$ per cent.
$Z_2=50$ per cent.

Then, applying equation (4),

$$3I_{a0}=\frac{3}{0.1+0.9+0.5}=2$$

The current is therefore twice the rated current.

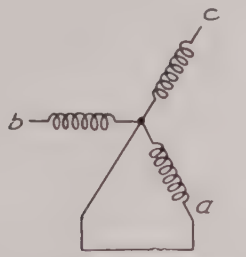


Fig. 9. Single Power Source, One Phase Grounded

Example 2

Two power sources (Fig. 10).

Let

$Z_{a0}=10$ per cent $\quad Z_{\alpha 0}=25$ per cent
$Z_{a1}=90$ per cent $\quad Z_{\alpha 1}=150$ per cent
$Z_{a2}=50$ per cent $\quad Z_{\alpha 2}=120$ per cent

Then we have,

$$I_0=10+4=14$$
$$I_1=1.11+0.67=1.78$$
$$I_2=2+0.83=2.83$$

and

$$I_e=\frac{I_0I_1I_2}{I_0I_2+I_0I_1+I_1I_2}=1.01$$

$$I_{a0}=\frac{10\times I_e}{I_0}=0.72 \qquad I_{\alpha 0}=\frac{4\times I_e}{I_0}=0.29$$

$$I_{a1}=\frac{1.11\times I_e}{I_1}=0.63 \qquad I_{\alpha 1}=\frac{0.67\times I_e}{I_1}=0.38$$

$$I_{a2}=\frac{2\times I_e}{I_2}=0.71 \qquad I_{\alpha 2}=\frac{0.83\times I_e}{I_2}=0.30$$

and

$$I_a=2.06 \qquad I_\alpha=0.97$$

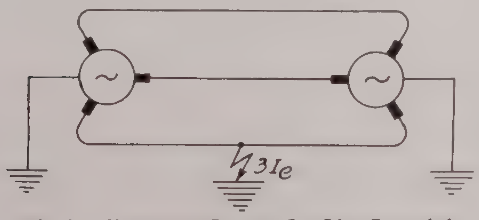


Fig. 10. Two Power Sources, One Line Grounded

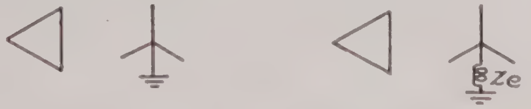
We see that the duty of the oil circuit breakers is greater than the three-phase short-circuit in this case.

Miscellaneous Remarks for Practical Calculations

The following remarks may be of assistance in making short-circuit calculations by the method of symmetrical co-ordinates.

(1) Y-connected symmetrical transformer bank (Fig. 11)

Suppose we have a Δ-Y-connected symmetrical transformer bank whose neutral is directly grounded. Then the zero phase sequence impedance of this transformer bank viewed from the Y side is Z, where Z is the impedance of one phase reduced to the terms of the secondary (or Y side). Positive and negative phase sequence impedances are also equal to Z.



Figs. 11a and 11b. Y-connected Transformer Bank

Instead of direct grounding, let the neutral be grounded through an impedance Z_e. Then the zero phase sequence impedance becomes $Z+3Z_e$, whereas the positive and negative phase sequence remain unchanged.

(2) Alternator stepped up with Δ-Y-connected symmetrical transformer bank

Suppose an alternator whose positive and negative phase sequence impedances are Z_1 and Z_2, referred to any arbitrary standard, is connected to a Y-bank of transformers as shown in Fig. 12. Then the impedances, viewed from the Y side, are as follows:

Zero phase sequence $=Z$
Positive phase sequence $=Z+Z_1$
Negative phase sequence $=Z+Z_2$

Other transformer banks, with isolated neutral, connected in parallel, do not alter the magnitude of the zero phase sequence impedance.

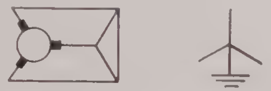


Fig. 12. Alternator and Δ-Y Transformer Bank

(3) Transformer bank with tertiary winding

Let the impedance of the primary, secondary and tertiary windings be Z_P, Z_S and Z_T.⁽⁷⁾ The connection for use with the calculating table should be made as shown in Figs. 13 and 14.

Fig. 13 illustrates the case in which the transformer is connected Δ-Y-Δ and Fig. 14 the case in which it is connected Δ-Y-Y.

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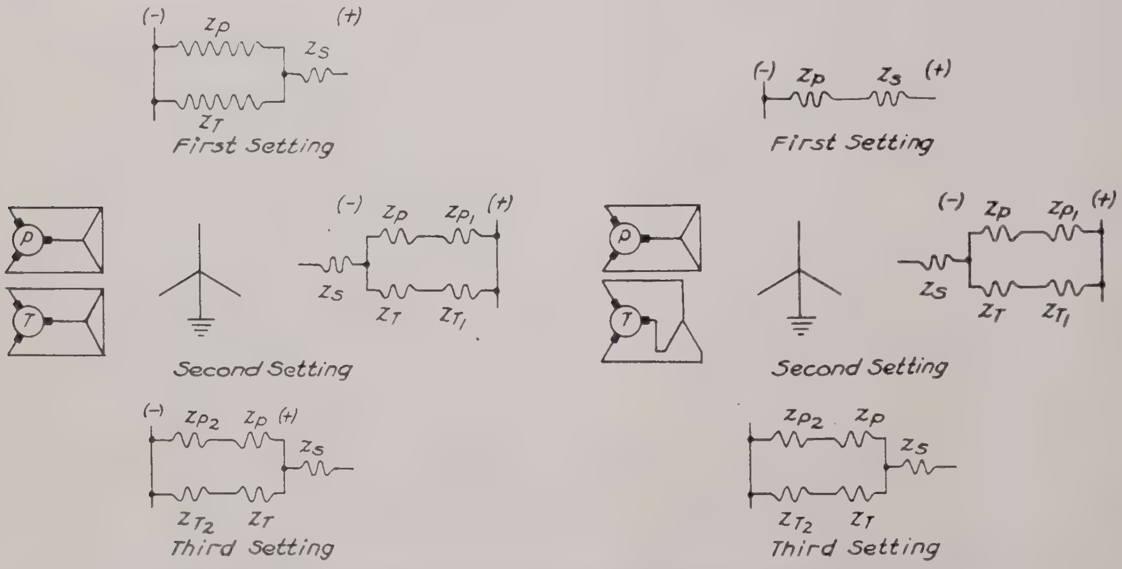
(7) A. Boyajian, *Journal A.I.E.E.*, April, 1925.

Appendix

Method used to measure the negative phase sequence impedance of the synchronous alternator

The positive phase sequence impedance of the synchronous alternator in the sustained state is the well-known synchronous impedance and it can easily be obtained from open-circuit and short-circuit tests on the machine.

The negative phase sequence impedance has an important bearing upon the phenomena accompanying the line-to-line short-circuit.



Figs. 13 and 14. Calculating Table Set-ups for Tertiary Winding Transformer Problems

The following method is proposed for measuring it directly in the sustained state by a simple test:

Drive the alternator at normal speed with two terminals b and c short-circuited. Measure the current I_b in the short-circuited phase and the voltage V_a between a, the open terminal, and b, the short-circuited terminal, for any field excitation. Then,

$$\frac{V_a}{I_b} = \sqrt{3}\, Z_2$$

The phase difference θ between V_a and I_b can be easily found and $\sin\theta$ is the power factor of Z_2.

Demonstration

Since b and c are short-circuited, we have(8)

$$I_{a1} = -I_{a2} = \frac{E_a}{Z_1+Z_2}$$

$$V_{a1} = V_{a2} = V_{a0} = \frac{Z_2 E_a}{Z_1+Z_2}$$

$$V_a = \frac{3\, Z_2 E_a}{Z_1+Z_2}$$

Furthermore, since V_{a0} is the potential of the generator neutral 0 above b, we have

$$V_a : V_{a-0} : V_{a0} = 3:2:1$$

$$I_b = (a^2 - a)\frac{E_a}{Z_1+Z_2} = -I_c$$

$$= -j\sqrt{3}\,\frac{E_a}{Z_1+Z_2}$$

Therefore, $$\frac{V_a}{I_b} = j\sqrt{3}\, Z_2$$

Calculation of Transient Current

For the purpose of calculating the transient current we must use the transient reactance. We know very little about magnitude of transient negative phase sequence reactance. If we consider that the instantaneous current for three-phase short-circuit and single-phase short-circuit are equal, we should take

$$Z_2 = (\sqrt{3} - 1)\, Z_1$$

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(8) *Trans. A.I.E.E.*, 1918, p. 1128.

Single-phase Short-circuit Calculations

By W. W. Lewis

Central Station Engineering Department, General Electric Company

There is no walk of life in which men are not constantly trying to shorten their work and provide themselves with tools which will enable them to produce more in a shorter time. Especially is this the case in engineering. In the technical side of the profession mathematicians are constantly at work to provide formulas and computing methods by which the designer and the men in the field may make laborious calculations short and of a routine nature. Into this class comes the problem of figuring out short-circuit currents in alternating current networks. Of three-phase and single-phase short-circuit currents, the latter are the more difficult to predetermine, and to make this work easier Mr. Bekku and Mr. Lewis each present a method of solution in this issue. Mr. Bekku's method applies to best advantage where power is fed into the network at many points and with the use of much apparatus. When the network is comparatively simple, Mr. Lewis' mode of attack gives the more rapid results. The present article gives Mr. Lewis' solution of the problem. Mr. Bekku's will be found on page 472.—Editor.

The calculation of currents caused by single-phase short circuits on three-phase networks is becoming more and more important, especially on grounded neutral circuits. Here the majority of short circuits occur from line to neutral and it is necessary to have some idea of the magnitude of the current in order properly to set relays and select oil circuit breakers.

A number of methods are available for calculating single-phase short circuits. The best method to use depends on the nature of the problem, as a method that is simple in one case may be unduly laborious in another.

In this article some of the methods will be discussed and examples given. The simplest kind of circuits only will be treated. Resistance will be neglected in accordance with the usual practice in three-phase short circuit problems.

Ohmic Method

The reactance of each circuit is expressed in ohms. The ohms are calculated as though for a three-phase problem, based on the actual voltage of the circuit, and then modified according to the ratio of transformation. In developing the formulas, the ratio of transformation phase to phase is considered to be 1:1.

The generator voltage, or that portion of it consumed in the short circuit, is equated to the sum of the voltage drops in each portion of the circuit. The circuit begins at one terminal, or the neutral of the generator, passes through the system to the short circuit and back over the return path to the same point on the generator.

An actual example will best illustrate the method. Fig. 1 represents a Y-connected generator and delta-Y step-up transformer. There is a single-phase line-to-line short circuit on the high tension side. The high tension voltage is E and the low tension 0.577 E by the 1:1 ratio of transformation. The reactance values are as designated and currents flow as indicated by the arrows.

The development of the equation is as follows:

$$2(0.866\times0.577E-3ix_1-3ix_2)=2ix_3+2ix_4$$

$$E=6ix_1+6ix_2+2ix_3+2ix_4$$

$$i=\frac{E}{6x_1+6x_2+2x_3+2x_4} \qquad (1)$$

Now assume that the high tension voltage is 110,000 volts and the low tension, 13,200 volts. Also assume the following reactance values:

x_1 = 0.7 ohm, 13,200 volts
x_2 = 2.08 ohms, 13,200 volts
x_3 = 39.1 ohms, 110,000 volts
x_4 = 9.07 ohms, 110,000 volts

Ratio of transformation = 63,500/13,200 = 4.81

Then the reactance values expressed in high tension equivalents will be

$$x_1 = 0.7 \times (4.81)^2 = 16.2$$
$$x_2 = 2.08 \times (4.81)^2 = 48.1$$
$$x_3 = \qquad = 39.1$$
$$x_4 = \qquad = 9.07$$

and

$$i=\frac{110{,}000}{6\times16.2+6\times48.1+2\times39.1+2\times9.07}$$

$$=\frac{110{,}000}{482.1}=228 \text{ amp.}$$

Another example will be given in order more thoroughly to fix in mind the method of solution. Fig. 2 represents the same system as Fig. 1, but now the short circuit is from line to neutral.

In this case we may write the following equation:

$$0.577E-2ix_1-2ix_2=ix_3+ix_4$$

$$0.577E=2ix_1+2ix_2+ix_3+ix_4$$

$$i=\frac{0.577E}{2x_1+2x_2+x_3+x_4} \qquad (2)$$

The voltage and reactance values are the same as for Fig. 1.

Then:

$$i=\frac{0.577\times 110{,}000}{2\times 16.2+2\times 48.1+39.1+9.07}$$
$$=\frac{63{,}500}{176.77}=360 \text{ amp.}$$

Percentage Method

The reactance values are expressed in per cent on a common three-phase base. They are then modified for the single-phase base by a factor depending on the actual current, reactance and voltage of the particular part of the circuit. The three-phase current must likewise be modified. In the example of Fig. 1, let

$x_1=12.0$ % based on 30,000 kv-a., three-phase
$x_2=35.8$ % based on 30,000 kv-a., three-phase
$x_3=9.7$ % based on 30,000 kv-a., three-phase
$x_4=2.25$% based on 30,000 kv-a., three-phase

In this case it happens that the factors are all unity, except for the high-tension current. Then the short-circuit current is:

$$i=\frac{100}{12+35.8+9.7+2.25}\times(0.866\times 157.5)$$
$$=\frac{100}{59.75}\times 136.4$$
$$=1.672\times 136.4=228 \text{ amp.}$$

For the circuit shown in Fig. 2, involving a line-to-neutral short circuit, the modifying factors are as given in Table II.

Multiplying the three-phase values of reactance and current by these factors we get:

$x_1=12\times 1.1155=13.86$
$x_2=35.8\times 1.155=41.4$
$x_3=9.7\times 1.732=16.8$
$x_4=2.25\times 1.732=3.9$
Current $=157.5\times 1.732=272.9$ amp.

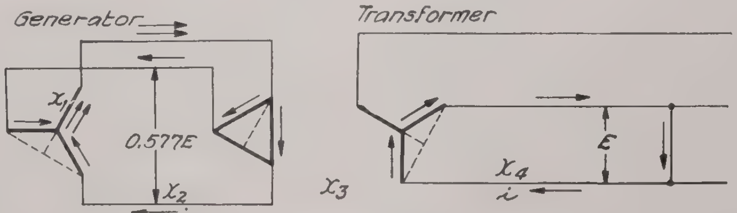

Fig. 1. Single-phase Line-to-line Short Circuit

The three-phase current corresponding to 30,000 kv-a. and 110,000 volts equals 157.5 amp.

The modifying factors to change the three-phase reactance and current values to single-phase are found as in Table I. The voltage *e* is the line-to-neutral voltage in all cases, both high and low tension.

TABLE I

	Three-phase	Single-phase	Factor 1-Ph./3-Ph.
x_1	$\frac{IX}{e}$	$\frac{I\times 1.5X}{1.5\,e}$	1
x_2	$\frac{IX}{e}$	$\frac{I\times 1.5X}{1.5\,e}$	1
x_3	$\frac{0.577\,I\times X}{e}$	$\frac{0.5\,I\times 2X}{1.732\,e}$	1
x_4	$\frac{0.577\,I\times X}{e}$	$\frac{0.5\,I\times 2X}{1.732\,e}$	1
H-t.-current	0.577 I	0.5 I	0.866

Then the short-circuit current equals:

$$i=\frac{100}{13.86+41.4+16.8+3.9}\times 272.9$$
$$=\frac{100}{75.96}\times 272.9$$
$$=1.318\times 272.9=360 \text{ amperes}$$

TABLE II

	Three-phase	Single-phase	Factor 1-Ph./3-Ph.
x_1	$\frac{IX}{e}$	$\frac{I\times 2X}{1.732\,e}$	1.155
x_2	$\frac{IX}{e}$	$\frac{I\times 2X}{1.732\,e}$	1.155
x_3	$\frac{0.577I\times X}{e}$	$\frac{IX}{e}$	1.732
x_4	$\frac{0.577I\times X}{e}$	$\frac{IX}{e}$	1.732
H-t.-current	0.577I	I	1.732

General Equation for Line-to-line Short Circuits

From the example under the percentage method involving the circuit of Fig. 1, we may write the following equations:

$$i=\frac{100}{x_1+x_2+x_3+x_4}\times 0.866\,I_n$$
$$=\frac{100\,I_n}{1.155\,(x_1+x_2+x_3+x_4)} \qquad (3)$$

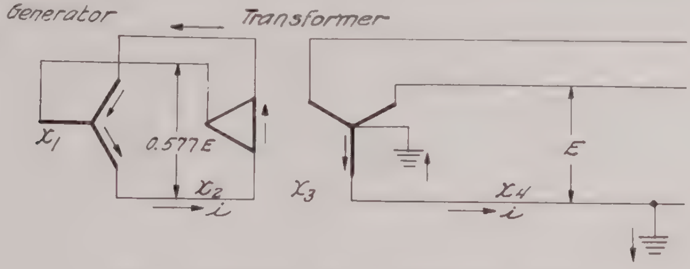

Fig. 2. Single-phase Line to Neutral Short Circuit

That is, the current in a line-to-line short circuit is equal to 100 times the normal three-phase current divided by 1.155 times the total per cent reactance of the circuit.

This equation applies to any line-to-line short circuit regardless of the extent of the circuit or of the transformations between the generators and the point of short circuit.

General Equation for Line-to-neutral Short Circuits

From the example under the percentage method involving the circuit of Fig. 2, we may write the following equation:

$$i=\frac{100}{1.155\,(x_1+x_2)+1.732\,(x_3+x_4)}\times 1.732\,I_n$$
$$=\frac{100\,I_n}{2/3\,(x_1+x_2)+(x_3+x_4)} \qquad (4)$$

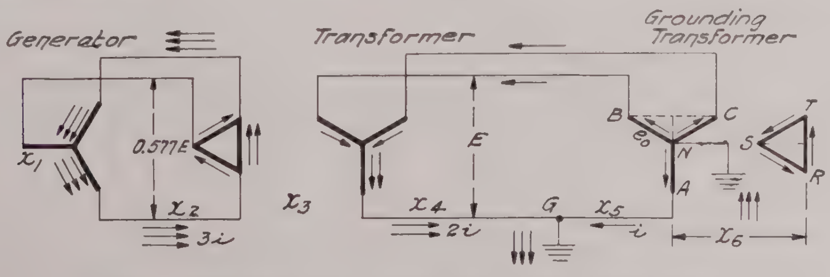

Fig. 3. Single-phase Line to Neutral Short Circuit. System neutral established by grounding transformer

That is, the short-circuit current is equal to 100 times the normal three-phase current divided by a quantity consisting of two-thirds the reactance in the circuit up to the grounded-neutral transformer plus the reactance of the grounded-neutral transformer and the grounded line, the reactance being expressed in per cent.

This equation applies to any line-to-neutral short circuit in which there is only one grounded-neutral transformer on the circuit on which the ground appears.

Grounding Transformers

Fig. 3 illustrates the case in which the transformer with grounded neutral is not the source of power, but which allows short circuit current to flow by virtue of its grounded neutral and closed delta. The process may be thought of somewhat as follows:

A ground at G causes the partial collapse of the voltage AN and current flows in the circuit NAG. This current is reproduced in the corresponding leg of the delta, calling for compensating currents in legs BN and CN. As reactance only is considered, the currents are all at right angles to the voltage AN, and the voltage drops are all in phase with the voltage AN. Due to the current flowing in the leg NB there is a drop in this leg, and the resultant voltage in the direction AN we may designate as e_o. The voltage e_o minus the drop through reactance x_6 appears across the leg RS. Likewise a similar voltage appears across leg TS. The sum of voltages RS and TS (always considering vertical components only) is the voltage TR. This is the voltage which forces current through the circuit NAG.

With these considerations in mind, we may write by the percentage method the following equations:

$$i=\frac{100}{1.155\ (x_1+x_2+x_3+x_4)+0.577\ (x_5+x_6)}\times 0.577\ I_n$$
$$=\frac{100\times I_n}{2\ (x_1+x_2+x_3+x_4)+x_5+x_6} \qquad (5)$$

Total ground current

$$3\ i=\frac{100\times I_n}{2/3\ (x_1+x_2+x_3+x_4)+\tfrac{1}{3}\ (x_5+x_6)} \qquad (6)$$

That is, the total short-circuit current flowing into the ground is equal to 100 times the normal three-phase current divided by two-thirds of the reactance from the generator to the ground point plus one-third of the reactance of the grounding transformer and the line reactance from the grounding transformer to the ground point, the reactance being expressed in per cent.

A very common application of the grounding transformer is illustrated in Fig. 4. In this figure there is a generating system feeding a bus which in turn sends power out onto feeders. It is desired to install a grounding transformer on the bus to establish a grounded neutral on the system. The equations for a short circuit on a feeder at the point A by the percentage method show the following relations:

$$i=\frac{100\ I_n}{2\ (x_1+x_2)+3x_3+(x_4+x_5)} \qquad (7)$$

or total ground current

$$3i=\frac{100\ I_n}{2/3\ (x_1+x_2)+x_3+\tfrac{1}{3}\ (x_4+x_5)} \qquad (8)$$

If x_3 is placed equal to zero this equation reduces to the same form as equation (6).

The usual method of procedure in selecting a grounding transformer on a circuit similar to that of Fig. 4, is as follows:

Assume the current required to give proper relaying on the system with a ground at the far end of the line at point A. Let us say that this is 2000 amp. and let us assume the following reactance values:

x_1 = 12 per cent on 25,000 kv-a., three-phase
x_2 = 3 per cent on 25,000 kv-a., three-phase
x_3 = 8 per cent on 25,000 kv-a., three-phase
x_4 = 0 per cent on 25,000 kv-a., three-phase
x_5 = To be found
Normal current = 1093 amp. at 13,200 volts.

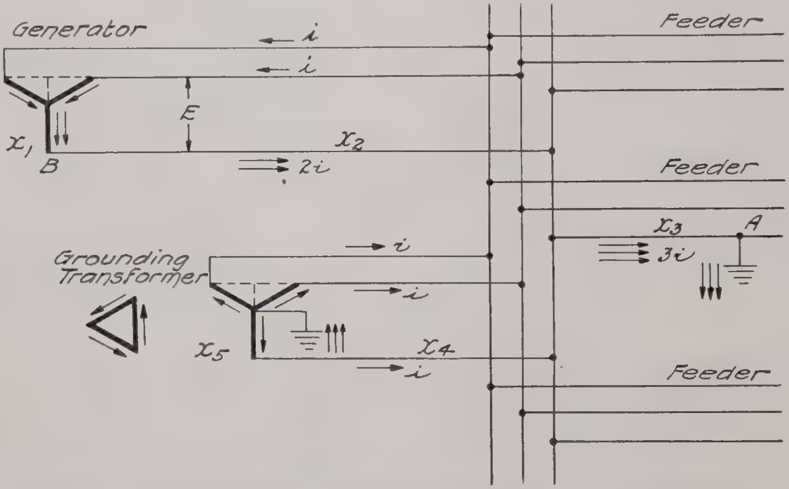

Fig. 4. Common Application of Grounding Transformer on Low Tension Bus

For equation (7) we may write the following equation for the reactance x_5:

$$x_5=\frac{100\ I_n}{i}-2\ (x_1+x_2)-3x_3-x_4 \qquad (9)$$

Substituting the assumed values of I_n, i and reactance in equation (9), we have

$$x_5=\frac{100\times 1093}{2000/3}-2\ (12+3)-3\times 8-0$$
$$=110 \text{ percent}$$

The maximum short-circuit current that the grounding transformer will have to stand will flow in case of a line ground just outside of the generator at B. In this case

$$x_2=0$$
$$x_3=0$$
$$x_4=3$$

Then from equation (8):

$$3i=2400 \text{ amp.}$$

The grounding transformer will have a reactance of 110 percent at 25,000 kv-a. and will be designed to carry 2400 amp. in the ground or 800 amp. in each leg on short circuit. Now let us assume a normal transformer with say 5-per cent reactance on its own rating. This gives $\frac{5}{110}\times 25{,}000 = 1136$ kv-a. or $\frac{1136\times 10^3}{13{,}200\times 1.73} = 49.6$ amp.

Therefore a transformer bank with a normal rating of 1136 kv-a. or 49.6 amp. with 5-percent reactance when installed on the system as shown in Fig. 4, would allow 2000 amp. short-circuit current to flow with a ground at *A* or 2400 amp. with a ground at *B*. Likewise a 10-percent reactance transformer of two times 1136 = 2272 kv-a. would perform the same function.

As an alternative to a Y-delta grounding transformer a zig-zag auto transformer may be used. The calculation may be performed for the Y-delta grounding transformer and a zig-zag auto transformer of similar characteristics may then be called for if desired.

Sometimes the transformer not only acts as a grounding transformer for one generating system but feeds current into the short circuit from another generating system connected to its own windings. Fig. 6 illustrates this case.

This problem may be solved by the ohmic method or by a percentage method, developed for three-winding transformers. The three-winding method is discussed in detail in the following paragraphs.

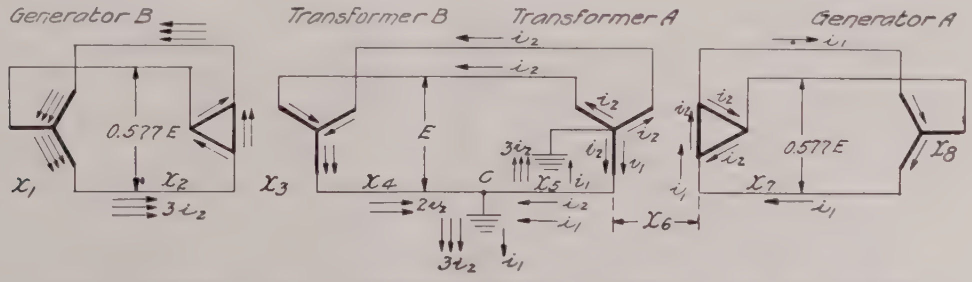

Fig. 6. Transformer *A* Acts as a Grounding Transformer for Generator *B*, and Feeds Into Short Circuit Directly from Generator *A*

Three-winding Transformers

Short circuits involving three-winding transformers may be solved by the ohmic method previously described or sometimes more simply by a percentage method given in a paper entitled, "Theory of Three-circuit Transformers," by A. Boyajian, *A. I. E. E. Journal*, April, 1924. The essence of Mr. Boyajian's method is as follows:

One phase or leg of the three-winding transformer (Fig. 5-a), may be represented by the equivalent circuit of Fig. 5-b. The reactance of the three legs of the equivalent circuit may be derived from the following equations:

$$X_{AC} = x_a + x_c \tag{10}$$

$$X_{AB} = x_a + x_b \tag{11}$$

$$X_{BC} = x_b + x_c \tag{12}$$

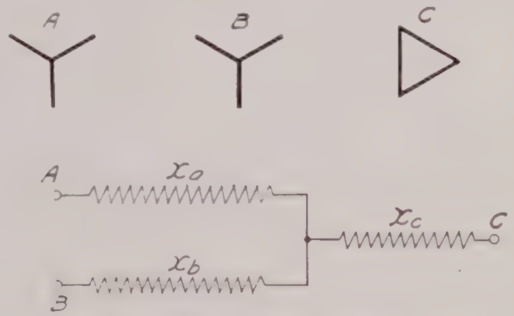

Fig. 5a and 5b. Three-winding Transformer and Equivalent Circuit

from which

$$x_a = \frac{X_{AB} + X_{AC} - X_{BC}}{2} \tag{13}$$

$$x_b = \frac{X_{AB} + X_{BC} - X_{AC}}{2} \tag{14}$$

$$x_c = \frac{X_{AC} + X_{BC} - X_{AB}}{2} \tag{15}$$

If power is fed from two sources *A* and *B*, into a short circuit at *C*, then the total reactance offered by the transformer is

$$X_t = \frac{1}{\frac{1}{x_a} + \frac{1}{x_b}} + x_c = \frac{x_a x_b}{x_a + x_b} + x_c \tag{16}$$

The short-circuit current if limited only by the transformer reactance is

$$I_{short}=\frac{100\times I_n}{X_t} \qquad (17)$$

The portions of the total current furnished by systems A and B are, respectively,

$$i_A=\frac{x_b}{X_{AB}}\times I_{short} \qquad (18)$$

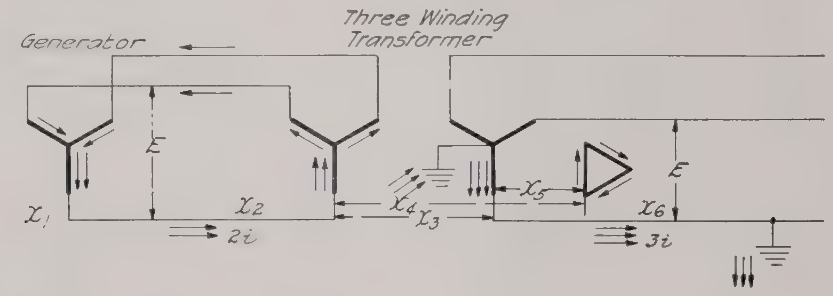

Fig. 7. Short Circuit on Three-winding Transformer. One source of power

$$i_B=\frac{x_a}{X_{AB}}\times I_{short} \qquad (19)$$

With these principles in mind let us examine a few cases involving three-winding transformers or in which the three-winding theory may be used. In the example of Fig. 6 there is no winding transformer proper but the three-winding theory nevertheless may be used. Let us assume the following reactance values in percent, on 30,000 kv-a., three-phase:

$x_1=12$

$x_2=35.8$

$x_3=9.7$

$x_4=2.25$

$x_5=3.42$

$x_6=20.3$

$x_7=35.8$

$x_8=12.0$

$I_n=394$ amp. at 44,000 volts

Then $X_{AC}=2/3\ (x_8+x_7)+(x_6+x_5)=55.59$

$X_{BC}=2/3\ (x_1+x_2+x_3+x_4)+1/3\ (x_5+x_6)$
$=47.74$

$X_{AB}=2/3\ (x_1+x_2+x_3+x_4)+2/3\ (x_5+x_6)$
$+2/3\ (x_7+x_8)=87.51$

$x_a=47.69$ by equation (13)

$x_b=39.84$ by equation (14)

$x_c=7.91$ by equation (15)

$X_{short}=29.56$ by equation (16)

$I_{short}=\frac{100}{29.56}\times 394=1335$ amp. by equation (17)

$I_A=608$ amp. by equation (18)

$I_B=727$ amp. by equation (19)

In Fig. 7 is shown a three-winding transformer with one source of power. A formula may be written by the percentage method as follows:

$$I_{short}=\frac{100\times I_n}{2/3\ (x_1+x_2+x_3)+1/3\ (x_5+x_6)} \qquad (20)$$

In this case the three-winding transformer formulas proper do not enter. If the following percent reactances hold good on 30,000 kv-a., 3-phase:

$x_1=2$

$x_2=2$

$x_3=8$

$x_4=13$

$x_5=4$

$x_6=5$

and

$I_n=1310$ amp. at 13,200 volts

then

$$I_s=\frac{100\times 1310}{14.33}=9150 \text{ amp.}$$

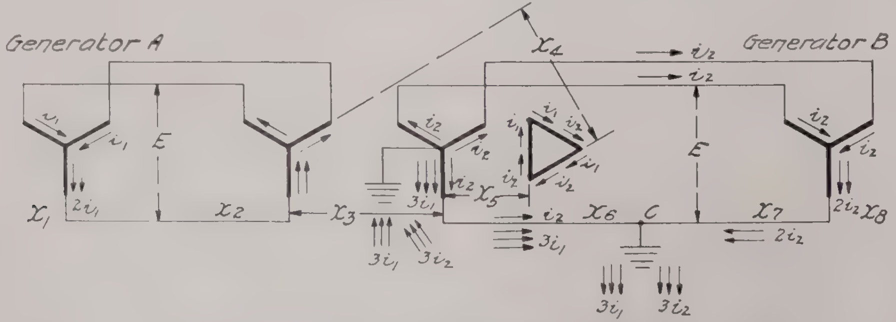

Fig. 8. Three-winding Transformer Acting as Grounding Transformer for Generator *B*, and Feeding Directly from Generator *A* Into Short Circuit

In Fig. 8 is shown a similar example with two sources of power and a three-winding transformer.

Assume the following values of reactance, in per cent at 30,000 kv-a., 3-phase:

$x_1 = 9.7$
$x_2 = 2.3$
$x_3 = 3.4$
$x_4 = 10.0$
$x_5 = 5.7$
$x_6 = 20.3$
$x_7 = 15.0$
$x_8 = 12.0$

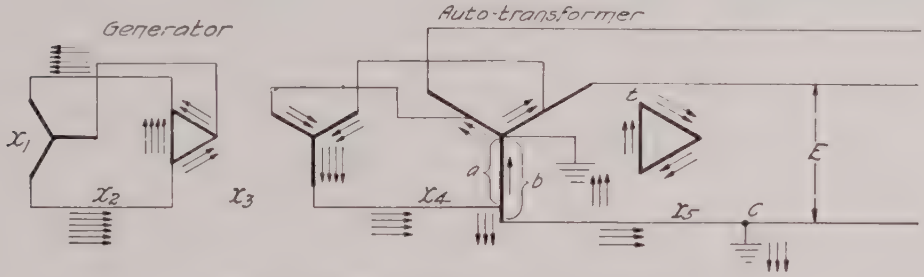

Fig. 9a. Typical Connection for an Auto-transformer

Equations may be written by the three circuit theory as follows:

$$X_{AC} = 2/3(x_1+x_2) + 2/3(x_3+x_6) + 1/3(x_5+x_6) = 32.47$$

$$X_{BC} = 2/3(x_7+x_8) + 1/3(x_5+x_6) = 26.66$$

$$X_{AB} = 2/3\ (x_1+x_2) + 2/3\ (x_3+x_6) + 2/3\ (x_7+x_8) = 41.8$$

$$x_a = \frac{X_{AB}+X_{AC}-X_{BC}}{2} = 23.81$$

$$x_b = \frac{X_{AB}+X_{BC}-X_{AC}}{2} = 18.0$$

$$x_c = \frac{X_{AC}+X_{BC}-X_{AB}}{2} = 8.67$$

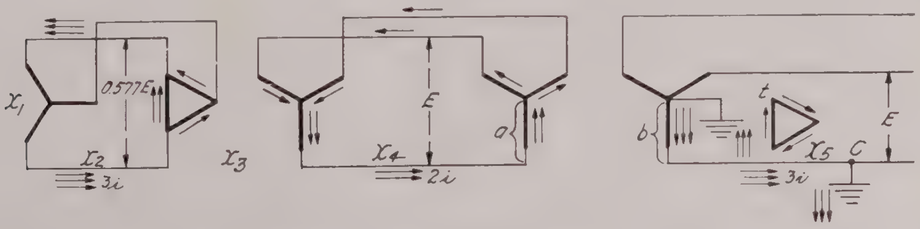

Fig. 9b. Equivalent Circuit of the Auto-transformer of Fig. 9a

$$X_{short} = \frac{1}{\frac{1}{x_a}+\frac{1}{x_b}} + x_c = 18.72$$

$$I_{short} = \frac{100}{X_{short}} \times I_n = 6930 \text{ amp.}$$

$$I_A = \frac{x_b}{x_a+x_b} \times I_{short} = 2980 \text{ amp.}$$

$$I_B = \frac{x_a}{x_a+x_b} \times I_{short} = 3950 \text{ amp.}$$

Auto-transformers

There is a large variety of auto transformer connections and combinations. In most cases the auto-transformer may be replaced by an equivalent transformer.

In an auto-transformer without tertiary, the reactance involved is that from the common winding to the series-common or total winding. If the auto-transformer has a tertiary, in addition to the reactance from common to the series-common windings there also comes in the reactance from common to tertiary and from series-common to tertiary.

Fig. 9 (a) shows a typical auto-transformer arrangement and Fig. 9 (b) shows the equivalent transformer connection,

The solution of this arrangement by equation (20) is as follows:

$$I_{short} = \frac{100\ I_n}{2/3\ (x_1+x_2+x_3+x_4+x_{ab}) + \frac{1}{3}(x_{bt}+x_5)} \quad (21)$$

Let $x_1 = 12$ percent on 30,000 kv-a., 3-phase:

$x_2 = 5$
$x_3 = 10$
$x_4 = 20$
$x_5 = 10$
$x_{ab} = 17$
$x_{at} = 20$
$x_{bt} = 16$

$I_n = 131$ amp. at 132,000 volts

Then

$$I_{short} = \frac{100 \times 131}{2/3(12+5+10+20+17) + 1/3 \times 16 + 10} = 226 \text{ amp.}$$

Special Cases

Two or more generators in multiple, one with grounded neutral

This case is illustrated in Fig. 10. All the ungrounded generators feed into the short circuit through the generator with grounded neutral.

From the figure we may write the following equations by the ohmic method:

Lower circuit:

$$0.577E = i_1 (x_1 + x_2 + x_5) + 2\, i_2\, x_5 \qquad (22)$$

Upper circuit:

$$0.577E = i_1\, x_5 + i_2\, (x_1 + x_2 + 3x_3 + 3x_4 + 2x_5) \qquad (23)$$

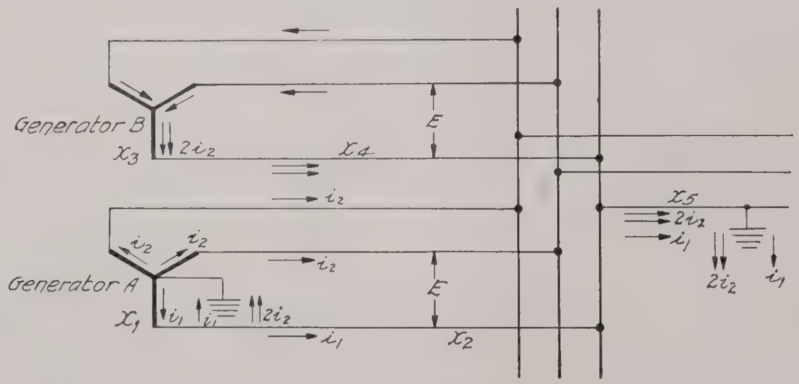

Fig. 10. Two or More Generators in Multiple, One with Grounded Neutral

Solving equations (22) and (23) simultaneously we get,

$$i_1 = \frac{0.577E \times B}{BC + 2A\, x_5} \qquad (24)$$

$$i_2 = i_1 \frac{A}{B} \qquad (25)$$

$$I_{short} = i_1 + 2\, i_2 \qquad (26)$$

in which

$$A = x_1 + x_2$$
$$B = x_1 + x_2 + 3x_3 + 3x_4$$
$$C = x_1 + x_2 + x_5$$

Assume that there is no reactance between generators A and B and that the short circuit is on the bus. In other words, x_2, x_4 and x_5 equal zero. Then we may work out the limit for i_2 as follows:

$$A = x_1$$
$$B = x_1 + 3x_3$$
$$C = x_1$$
$$i_1 = \frac{0.577E}{x_1}$$
$$i_2 = i_1 \times \frac{x_1}{x_1 + 3x_3}$$

When $x_3 = 0$ (in other words infinite generator capacity at B), then $i_2 = i_1$ and the total current in the ground equals $3i_1$. When x_3 equals infinity (i. e., no generating capacity at B), then i_2 equals zero and the total current in the ground equals i_1.

Two or more transformers in parallel, one with grounded neutral

Fig. 11 illustrates this case. Current is fed into the short circuit not only directly through transformer "A" which has a grounded neutral, but through transformer "B" also, "A" acting as a grounding transformer. From the figure we may write the following equations by the ohmic method:

Lower circuit:

$$0.577E = i_1\, (2x_1 + 2x_2 + x_6 + x_7 + x_8 + 2x_9) + i_2\, (6x_1 + 6x_2 + 3x_6 + x_7 + x_8)$$
$$= i_1\, A + i_2 B \qquad (27)$$

Upper circuit:

$$0.577E = i_1\, (2x_1 + 2x_2 + x_6 + \tfrac{1}{3}\, x_7 + \tfrac{1}{3}\, x_8) + i_2\, (6x_1 + 6x_2 + 6x_3 + 2x_4 + 2x_5 + 3x_6 + x_7 + x_8$$
$$= i_1 C + i_2 D \qquad (28)$$

Solving equations (27) and (28) simultaneously, we get

$$i_1 = 0.577E \times \frac{D - B}{AD - BC} \qquad (29)$$

$$i_2 = i_1 \times \frac{A - C}{D - B} \qquad (30)$$

$$I_{short} = i_1 + 3i_2 \qquad (31)$$

Modifications in Reactance in Practical Circuits

Generator Reactance:

The reactance of a generator for a single-phase short circuit is different from that for a three-phase short circuit due to a change in the flux conditions. Two methods by which current can flow in a Y-connected generator under single-phase short-circuit conditions are shown in Figs. 1 and 2. According to Mr. E. G. Merrick's investigations, for the condition of Fig. 1 the single-phase instantaneous generator current will equal 1.155 times the three-phase current, and for the condition of Fig. 2 the single-phase instantaneous generator current will equal the three-phase current. A third method in which current can flow is shown in Fig. 12. In this case the instantaneous single-phase short-circuit current is 1.5 times the three-phase current.

From these relations we can find the following factors by which the ordinary instantaneous line-to-neutral reactance must be multiplied to obtain the correct reactance in instantaneous single-phase short-circuit problems:

INSTANTANEOUS SHORT CIRCUITS

Generator Connection	Current Distribution	Multiplier
Y	1-0-0	0.666
Y	1-1-0	0.866
Y	1-1-2	0.866

For sustained short circuit the effect is somewhat different for generators with salient field poles, such as waterwheel generators, and for generators with distributed field windings, such as turbine-generators and synchronous condensers.

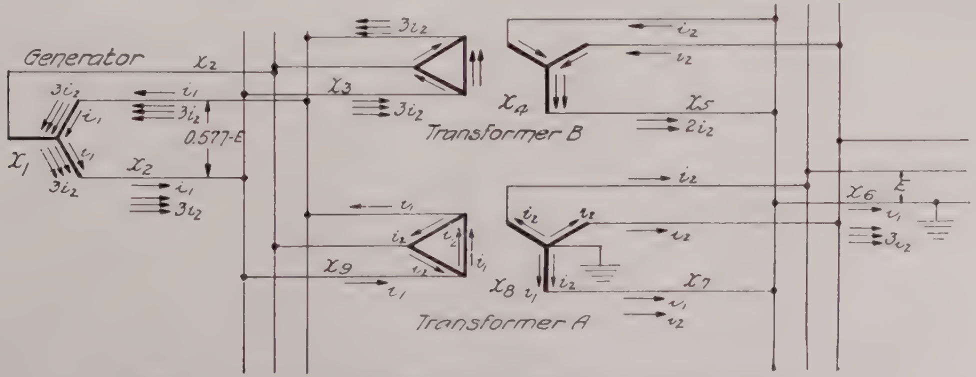

Fig. 11. Two or More Transformers in Parallel, One with Grounded Neutral

For the current distribution of Fig. 1 the sustained single-phase generator short-circuit current equals 1.47 times the three-phase current for salient-pole machines and 1.73 times the three-phase current for distributed-pole machines. For the distribution of Fig. 2 the sustained single-phase generator current equals 1.277 times the three-phase current for salient-pole machines and 1.5 times the three-phase current for distributed-pole machines.

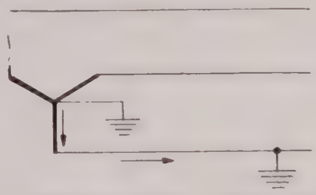

Fig. 12. Single-phase Line to Neutral Short Circuit on Generator. Current in One Phase Only

For the condition of Fig. 12 the sustained single-phase short-circuit current equals two times the three-phase current for salient-pole machines and 2.5 times the three-phase current for distributed-pole machines. From these relations we may derive the following factors by which the ordinary line-to-neutral sustained reactance should be multiplied in solving single-phase short-circuit problems:

SUSTAINED SHORT CIRCUITS

Generator Connection	Current Distribution	Multiplier for Salient Pole Machines	Multiplier for Distributed Pole Machines
Y	1-0-0	0.5	0.4
Y	1-1-0	0.677	0.577
Y	1-1-2	0.677	0.577

Line Reactance

For a single-phase short circuit from line to neutral, one conductor grounded, the reactance of this conductor is greater than the normal three-phase reactance. The actual value depends on soil and other local conditions and must be determined by test.

Some tests were made in 1921 on the Alabama Power Company's 110-kv. 60-cycle line between Lock 12 and Bessemer, a distance of 39.8 miles. The circuit was one of two carried on the same towers, the conductors being 2/0 copper spaced 10 feet vertically. Fig. 13 shows the arrangement of the conductors at the towers.

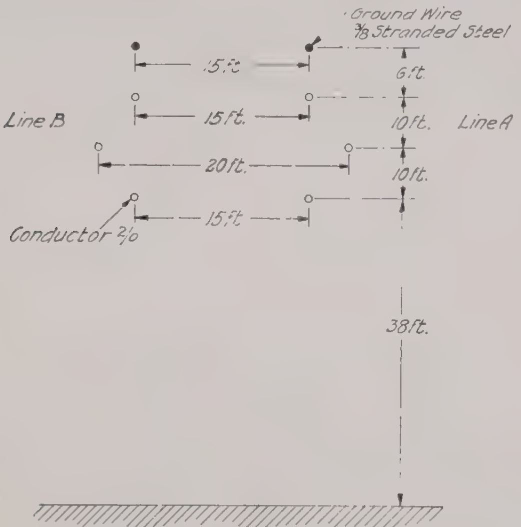

Fig. 13. Alabama Power Co., 110,000-volt, 60-cycle Circuits from Lock 12 to Bessemer. Line *B* under test. Line *A* carrying load

Table III gives the results of tests with the four following arrangements of conductors:

(a) Ordinary three-phase arrangement, no conductors grounded.

(b) Three conductors in multiple with ground return.

(c) Two conductors in multiple with ground return.

(d) One conductor with ground return.

A similar set of tests was made on the system of the Northern States Power Company in Minnesota, in 1922. Fig. 14 shows the arrangement of the conductors. The line was rated 13,200 volts, 60 cycles and extended from Riverside to Coon Rapids, a distance of 10.1 miles. The conductor was 4/0 copper for 6,000 ft. and 250,000 c.m. copper for 47,500 ft. Only two tests were made, *i.e.*, one with the three-phase arrangement and the other with one conductor and ground return. Table IV gives the results.

In 1915 a series of tests was conducted on the system of the Pennsylvania Water & Power Company extending from Holtwood to Highlandtown (Baltimore), a distance of 40 miles. This is a 70,000-volt, 25-cycle line, the conductors being 300,000-c.m., 19-strand aluminum, spaced 9 ft. apart vertically. The results of the test are given in Table V.

The figures for the tests on the three systems are averaged in Table VI.

From these averages it will be seen that the reactance of one conductor with ground return is about double the ordinary reactance of one conductor in three-phase arrangement. This value depends somewhat on the radius of the conductor but more on the depth of the ground return. In the case of three conductors in multiple or two conductors in multiple with ground return, the spacing between the conductors is also a factor. If the spacing is small then the condition of one conductor with ground return is approached and the reactance of both of these arrangements approaches twice that of the ordinary three-phase arrangement. On the other hand if the conductors are spaced far apart, then the reactance with ground return would approach that of the ordinary three-phase arrangement.

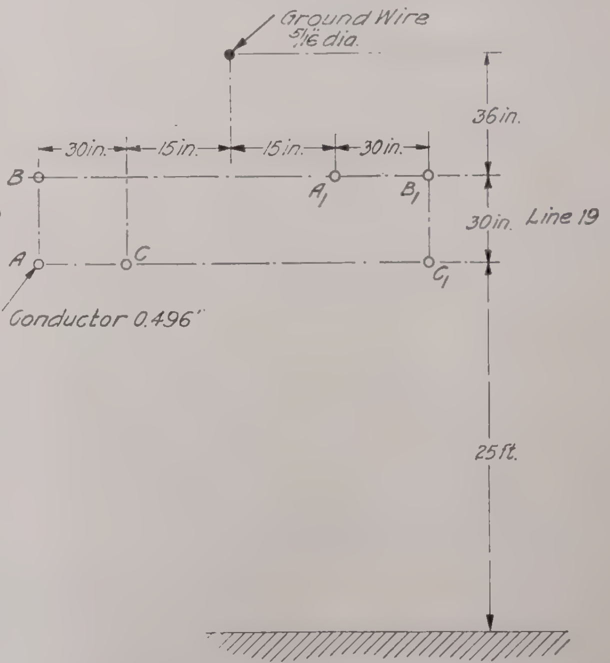

Fig. 14. Northern States Power Co., 13,200-volt, 60-cycle circuits from Riverside to Coon Rapids. Line 20 under test. Line 19 carrying load

We usually think of the ground surface as forming the neutral plane in arrangements with conductors and ground return. As a matter of fact the neutral plane may be a considerable distance below the ground surface. Mr. D. S. Snell has made some calculations from the data given in Tables III, IV and V for one conductor with ground return and has found that the neutral plane is from 240 to 3220 ft. below the ground surface. As this distance enters the formulas for the calculation of inductance as a logarithm, he has taken the logarithmic average of the distance and finds this to be about 1000 ft. If these tests are characteristic we may therefore calculate the inductance of one conductor with ground return from the formula

$$L = 0.74 \log_{10}\frac{D}{r} + 0.0805 \text{ mh. per mile}$$

in which D = distance from conductor to image, approximately 24,000 inches, and r = radius of conductor in inches.

In calculating single-phase short circuits with ground return, sometimes the reactance of one conductor to ground enters the calculation and sometimes the reactance of three conductors in multiple with ground return. For example: In Fig. 2 it is obviously a case of one conductor with ground return. In Fig. 3 as far as x_5 is concerned the currents in all three conductors are equal and in the same direction, *i.e.*, we have the case of three conductors in multiple with ground return. As far as x_4 is concerned, equal currents are coming in on two conductors and their sum is going out on the third. Therefore the ground does not enter and the ordinary three-phase reactance from line to neutral is used.

In Fig. 5 as far as x_4 is concerned we have the ordinary three-phase reactance. The case of x_5 is not so obvious. As far as i_2 is concerned we have three conductors in multiple with ground return. As far as i_1 is concerned, we have one conductor with ground return. A compromise between these conditions must be reached, perhaps an average value of reactance assumed, say 175 percent of normal.

In the case of line-to-line short circuits, of course the ground does not enter and the ordinary three-phase reactance is used.

It will thus be seen that the line reactance must necessarily be an approximate quantity owing to the variations in the depth of the neutral plane for different localities and the

TABLE III

SHORT-CIRCUIT TESTS—ALABAMA POWER COMPANY

Arrangement	Impedance Ohms	Resistance Ohms	Reactance Ohms	Per Cent of Three-phase Reactance
Three phase, one conductor to neutral, no ground	38.1	16.4	34.4	100
Three conductors in multiple, ground return	40.34	6.63	39.8	115.5
Two conductors in multiple, ground return	47.9	9.42	47.0	136.5
One conductor, ground return	66.5	17.98	64.0	186.0

Line Data:

Length: 39.8 miles
110,000 volts
60 cycles
2/0 stranded copper conductor

Spacing, 10 ft., vertical
Height of bottom conductor from ground, 38 ft.
Normal sag, 10 ft.
Two ground wires of 3/8 in. stranded steel

TABLE IV

SHORT-CIRCUIT TESTS—NORTHERN STATES POWER COMPANY

Arrangement	Impedance Ohms	Resistance Ohms	Reactance Ohms	Per Cent of Three-phase Reactance
Three phase, one conductor to neutral, no ground	6.67	2.37	6.24	100
One conductor with ground return	13.35	3.9	12.77	205

Line Data:

Length: 10.1 miles
13,200 volts
60 cycles
4/0 stranded copper for 6,000 ft.

250,000-c. m. stranded copper for 47,500 ft.
Spacing 30 in.—30 in.—42.5 in. (L-cross-section).
Height of bottom conductor from ground, 25 ft.

manner in which the various currents circulate through the conductors and ground.

Method of Symmetrical Co-ordinates

Mr. S. Bekku in a paper in this number of the Review develops a method of calculating single-phase short-circuit problems by the use of the method of symmetrical coördinates or components. Mr. Bekku's method may be applied to all problems of this sort and in the complicated cases it is much less laborious than the methods given in the present article. In the case of the simpler problems the contrary may be true. It is well to know both methods and use the one that seems better for the individual case.

TABLE V

SHORT-CIRCUIT TESTS—PENNSYLVANIA WATER AND POWER COMPANY

Arrangement	Impedance Ohms	Resistance Ohms	Reactance Ohms	Per Cent of Three-phase Reactance
Three phase, one conductor to neutral, no ground	17.9	12.78	12.55	100
Three conductors in multiple, ground return	20.47	6.34	19.5	155
Two conductors in multiple, ground return	23.5	8.97	21.72	173
One conductor, ground return	31.4	14.86	27.65	221

Line Data:

Length: 40 miles
70,000 volts
25 cycles
300,000 c. m. aluminum conductor

Spacing, 9 ft. vertical
Height of bottom conductor from ground, 44 ft.
Normal sag, 18 ft.
Two ground wires

TABLE VI

SUMMARY—COMEINED RESULTS OF FIRST THREE TESTS

Arrangement	Percent of Three-phase Reactance Average of Tests on Three Systems
Three phase, one conductor to neutral, no ground	100
Three conductors in multiple, ground return	135
Two conductors in multiple, ground return	155
One conductor, ground return	204

Automatic Substations on the Melbourne Suburban Railway System, Australia

By R. M. Harvey

Substation Engineer of the Victorian Railways

We had hoped to include this article in our special Automatic Station Issue last month but were unable to do so because a misunderstanding of our closing date resulted in its arrival too late. It presents an example of automatic equipment applied to the control of some 8000 kw. of 1500-volt direct-current railway substation apparatus. In addition to the information given on operating performance, costs, etc., the description of this installation holds considerable interest for American engineers because of the features in which it parallels and those in which it departs somewhat from the general practice in this country.—Editor.

General

The railways of Victoria are owned and operated by the State Government. In 1913 it was decided to electrify the whole of the lines radiating from Melbourne to the outer suburbs. Owing to the war, this work was greatly delayed and the first electric train was not put into service until May, 1919. At the date of writing, the whole of the lines shown in Fig. 1 are electrified, making a total of approximately 360 miles of single track including sidings.

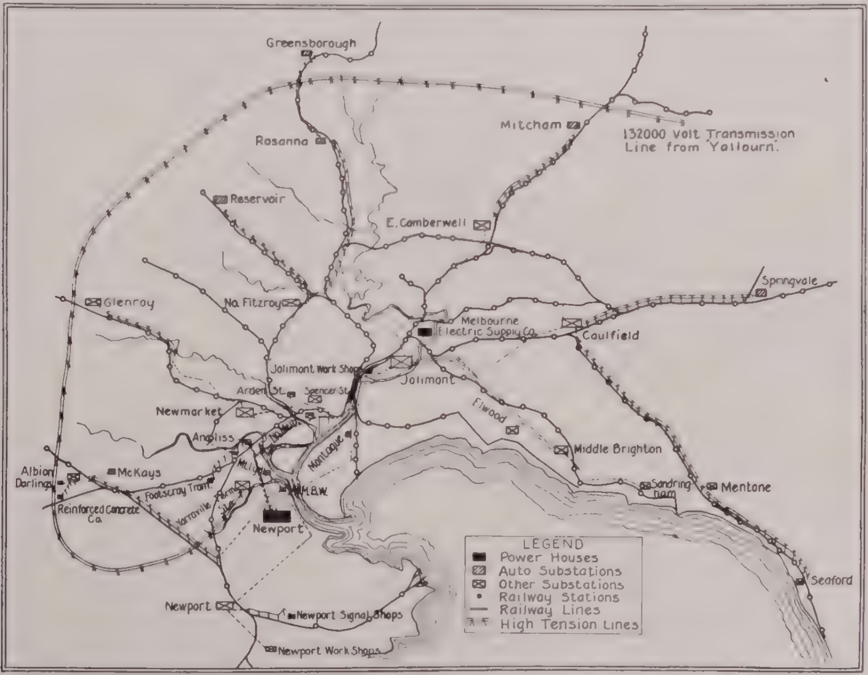

Fig. 1. Map of the Melbourne Suburban Electrification

At present, there are 16 substations in operation and two more will be completed by the end of this year. Of the existing substations, five are completely automatic. Three of these are double-unit substations and two single-unit. The double-unit substations are situated at Reservoir, Mitcham, and Springvale, and the single-unit ones at Greensborough and Rosanna. In each case a unit consists of a 1000-kw. continuous capacity 1500-volt synchronous converter with the necessary transformer and automatic switching equipment. The substation buildings are of concrete with a flat concrete roof and are in two parts. The larger portion contains the synchronous converters and automatic equipment, and at the rear of this is a smaller part or annex containing an auxiliary transformer and equipment. Beneath the bay containing the synchronous converters and equipment is a basement 4 ft. 6 in. high in which all cables and wiring are carried in porcelain cleats bolted to the floor above. Figs. 2 and 3 show layout diagrams of a double-unit substation, and Fig. 4 shows a rear view of such a substation with the annex.

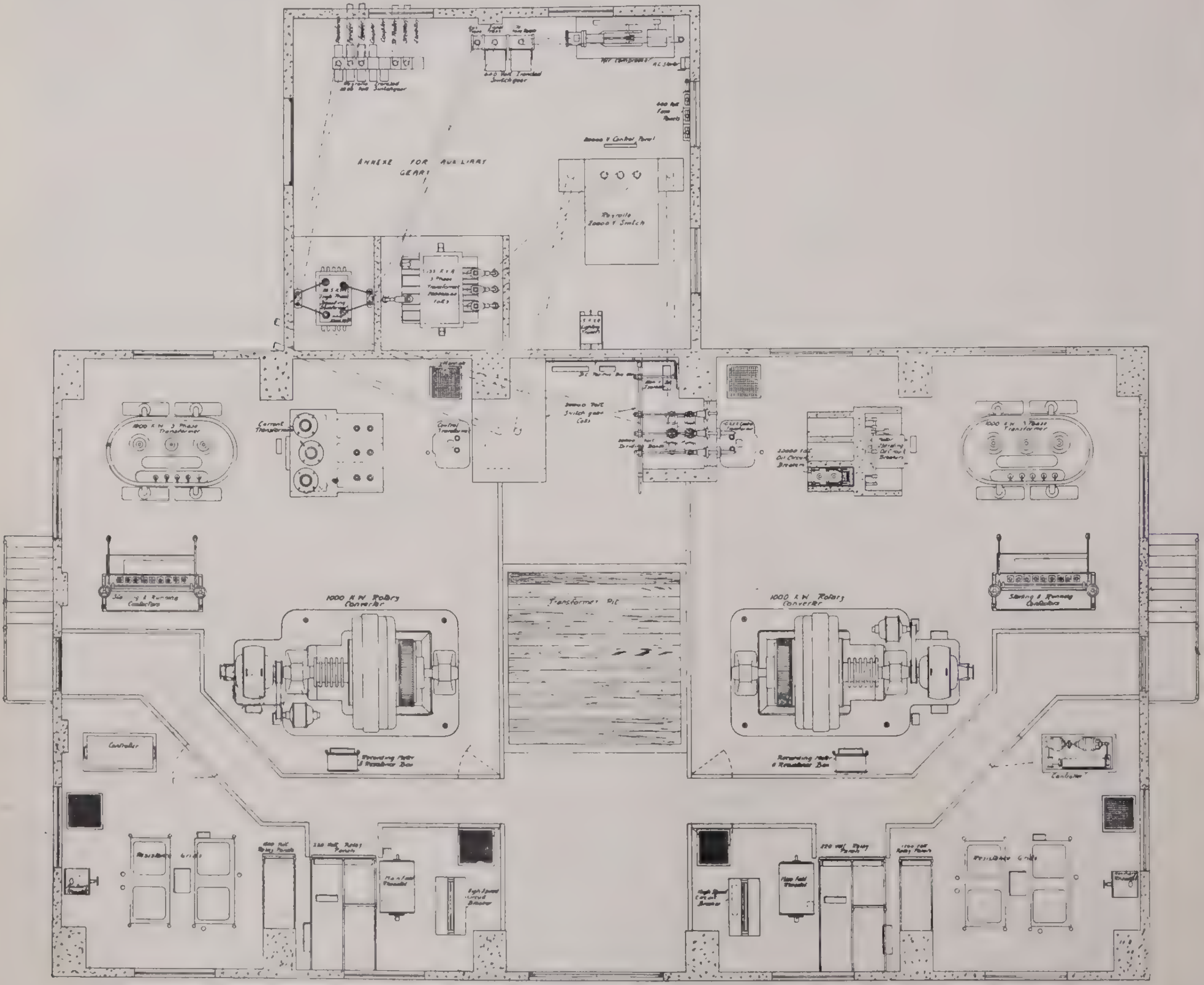

Fig. 2. Plan of the General Arrangement Used for a Double-unit Automatic Substation on the Melbourne Suburban Electrification

The high-tension supply to these substations is at 20,000 volts, 3 phase, 25 cycles, and is transmitted by overhead lines which terminate on steel structures on the railroad track outside the substation. From this structure, underground cables run to the high-tension cubicles in the substation. Above the 20,000-volt cable potheads inside the substation are the isolating switches operated through wood rods by means of a shaft and handle. The 1500-volt direct-current isolating switch is also operated by the same shaft. The handle operating the isolators is interlocked with the main oil switch and with the gates in the barrier surrounding the synchronous converter and equipment. It is impossible to open the isolators without opening the oil switch first. The opening of the isolators releases a key which may be seen projecting from the box above the handle in Fig. 5. This key unlocks the barrier gates and prevents the closing of the isolators until the gates are closed and locked and the key placed in the box. The isolators are connected to the main oil switch by copper tube conductors. On the line side of the oil switch, a 10-kv-a. single-phase control transformer is connected to two of the phases through expulsion fuses. This transformer supplies current for operating the main oil switch, the starting and running contactors, and certain other devices.

The main transformer is of the oil-insulated self-cooled type and has a capacity of 1080 kv-a. From the secondary terminals of the transformer, varnished-cambric flame-proof braided cable conveys current to the starting and running contactors, to the starting motor, and to the slip-rings of the synchronous converter.

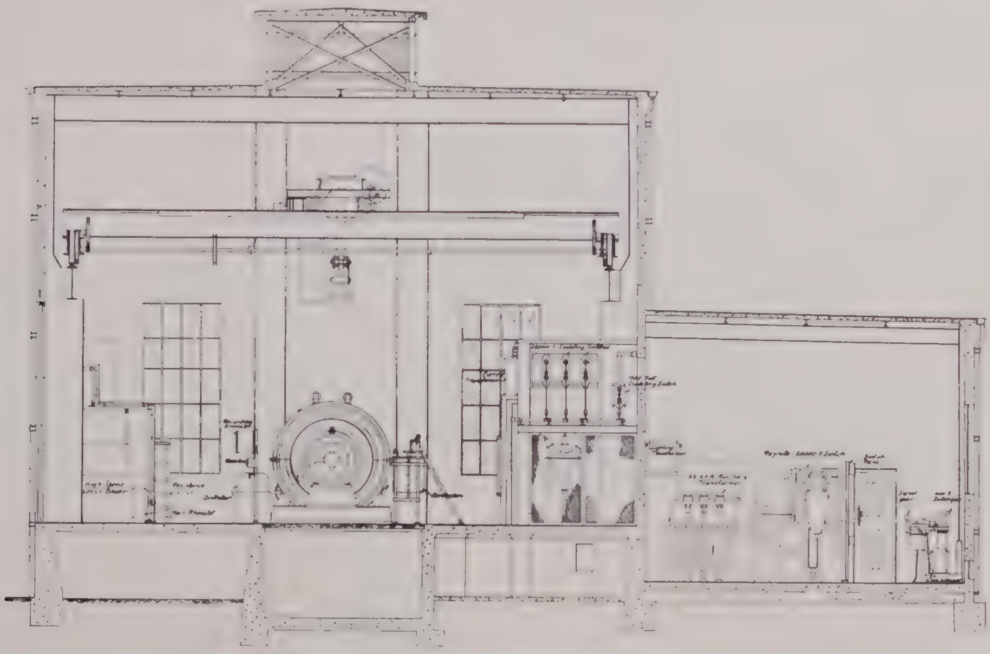

Fig. 3. Elevation of the Double-unit Substation Shown in Fig. 2

Each starting and running contactor (Fig. 9) consists of a three-pole unit mounted on a marble slab and immersed in oil. Above the tank containing these contactors is a slate slab carrying the full-field contactor, the auxiliary-field contactor, and the synchronizing-field contactor.

From the positive brush of the synchronous converter, current is led by varnished-cambric flame-proof cable through the high-speed circuit breaker, the load-limiting resistors and contactors, and an air-break circuit breaker to an isolator and so to the train contact wire. The negative brush of the converter is connected to the track rails. The direct-current switch gear is mounted in proximity to the relay panels.

Automatic Operation

The sequence of operation of the automatic equipment is as follows:

When a drop of voltage in the trolley wire occurs, the master starting element which is a contact-making voltmeter releases its armature. If low voltage continues longer than the setting of the time-delay starting relay, a master control contactor is closed. This in turn starts a motor-driven controller which closes the main oil switch and the starting contactor and then pauses. Under the influence of the starting motor the converter runs up to speed. A small direct-current generator belted to the shaft of the synchronous converter supplies excitation current to a separate winding on the converter field poles. This insures correct polarity of the converter. The building up of the exciter voltage causes the starting field contactor to close and adjust the converter field to the correct point for synchronizing. When synchronism is reached the voltage across the starting-motor winding falls, releasing the armature of the synchronizing relay. This relay restarts the controller which closes the running contactor. The windings of the starting motor are now short circuited and the slip-rings of the converter are connected directly to the transformer by the running contactor. The controller next closes the full-field contactor, also the high-speed circuit breaker and the main direct-current contactors. The converter is now connected to its load through the limiting resistors. If the current taken through the resistors is not excessive these are now short-circuited automatically.

The converter and its transformer are protected against overheating by overload relays on the alternating-current side and by special thermal relays. Short-circuits on the direct-current side cause the high-speed breaker to open. The opening of the high-speed breaker trips the main direct-current contactors, whereupon the high-speed breaker recloses. Should the overload persist, the limiting resistors heat up and operate thermostats which open the control circuit until the resistors cool down. Thermostats are fitted to all bearings and in the windings of the starting motor. When these operate they must be reset by hand before the converter can again be run up. The converter is fitted with an overspeed device which must also be reset by hand after it has operated. A prolonged starting period due to the failure of any part to function properly is guarded against by a relay which commences to time when the starting switch closes. If the starting operation takes normal time, this relay is cut out before it completes its stroke. If the starting period is abnormally long, this relay completes its stroke and locks the machine out. When the load on the converter drops below a certain value for a time exceeding the setting of the time-delay stopping relay, the machine is shut down until another load demand takes place.

The second converter in a double-unit substation is brought into operation when the load of the first machine is excessive. It shuts down again when the load on the station becomes less than that requiring two machines. In case the machine scheduled to start up first in a double-unit substation should fail to do so from any cause, the equipment as originally designed did not bring in the second unit.

The Railway Department's engineers have, therefore, added a relay which commences to time directly, the master starting element operates to start up the station. Should the first unit not be on load in normal time, this relay closes its contacts which are in parallel with those of the relay normally used to bring on the second unit when the load exceeds that of one converter. Either converter is, therefore, able to respond to load demand irrespective of whether it has been selected to start up by voltage drop or excess current.

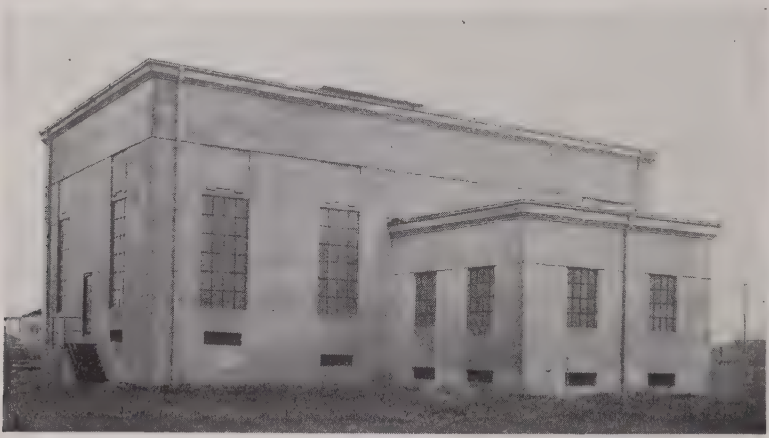

Fig. 4. Rear View of the Reservoir Double-unit Substation, Showing the Annex That Contains Auxiliary Equipment

In every case the automatic substations are placed at the outer end of lines, the manual substations occupying the inner area. Greensborough and Rosanna substations are located on the same line. Rosanna is located 4½ miles beyond the nearest manual station and Greensborough 4½ miles further out. Beyond Heidelberg, which is on the "down"(1) side of Rosanna substation, the service is less frequent.

The maximum number of trains to and from Heidelberg during one hour is eleven. The maximum number passing Greensborough per hour is four. The equipment at Rosanna substation is set to run up the converter with a contact-wire voltage of 1400 or less persisting for 25 sec. The equipment at Greensborough is set to cut in at 1300 volts or less persisting for 25 sec. With these settings, Greensborough substation does not cut in except for trains going beyond Rosanna. Rosanna substation runs practically all day, while Greensborough cuts in and out for every train.

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(1) The side away from Melbourne. Trains leaving the city are called "down" trains and those arriving "up" trains.—Ed.

In addition to the full automatic features, a three-core pilot cable is run from each unit to the nearest railway station office. The station master or signalman can, on instructions from the control engineer, cut in or out either unit in the substation. This method of starting is made use of to cut in the converter at Greensborough before a train leaves Eltham which is the terminus of the electrified section. This is done to prevent low rail potential during the interval between the train commencing to take power and the converter getting on load. This time is approximately 80 sec. made up of 25 sec. relay setting and 55 sec. running-up period.

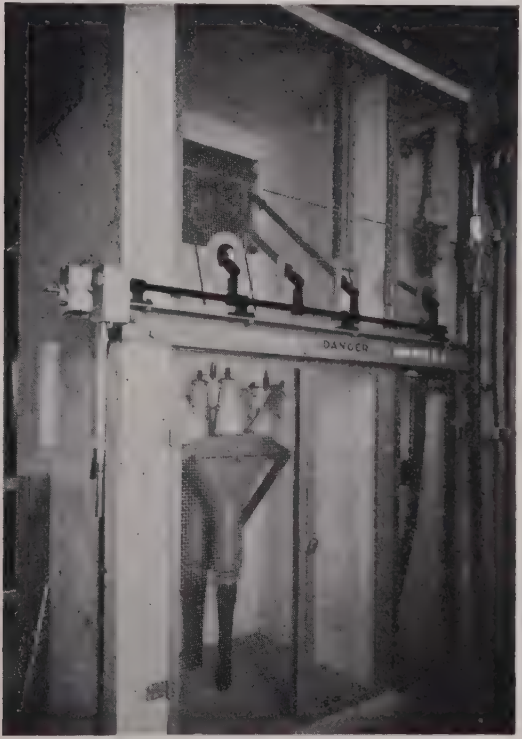

Fig. 5. Cable Potheads Inside the Substation, Together with Isolating Switches and Protecting Barriers

An indicating system showing by means of lamps the state of the converter and equipment, i.e., whether running or faulty, is also installed in the station master's office. The control engineer can therefore be informed as soon as a fault causing a shut-down occurs.

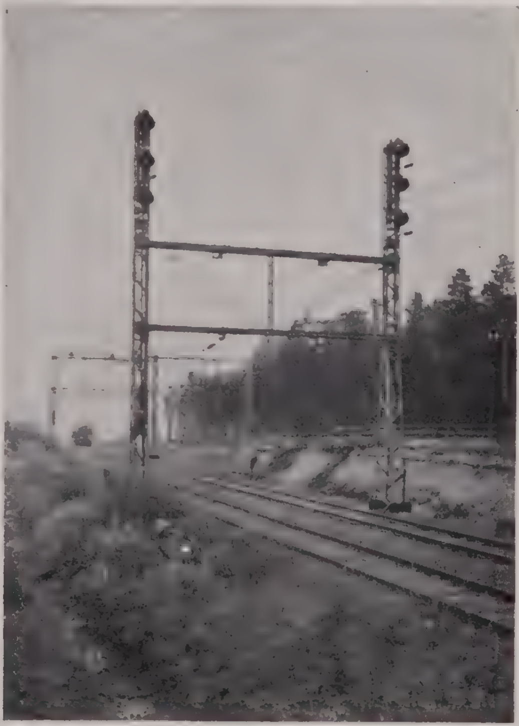

Fig. 6. Tensioning Structure for 1500-volt Direct-current Contact Wire. This bridge also carries the outdoor 20,000-volt cable potheads at which the transmission lines terminate outside the substation

The question of supervisory control is being considered with a view to its possible adoption at some future date when operating conditions warrant. As originally built, each unit in a substation was fitted with a multi-pen recording instrument intended to register each operation of 17 of the devices comprising the equipment. These recorders have been replaced by recording ammeters and cyclometer type counters on the devices.

It may be mentioned here that seven of these units operate about 620 times per annum, while the Greensborough converter cuts in 3845 times in the same period. Further data on the operation of the stations are given in Table I.

In addition to the five automatic substations now in operation, it is intended to convert one of the existing manual stations to automatic working during the current year.

During the same period two new single-unit automatic stations will be erected for the extension of the electrified system to Lilydale and Fern Tree Gully. The stations will be fully automatic and will consist of mercury-arc rectifiers, each station having a continuous capacity of 900 kw. with a two-hour overload of 50 per cent. The Department's engineers consider that this type of plant has reached a stage of development which warrants its trial on a fairly large scale.

Supervision and Maintenance

The development of the automatic substation has been brought about by economic causes. No account of any installation such as this is complete, therefore, without a statement regarding the costs of running as compared with those of manual stations.

As this particular installation was made during the unsettled conditions following the war, a statement of capital cost is of little value. As is well known, however, the auto-

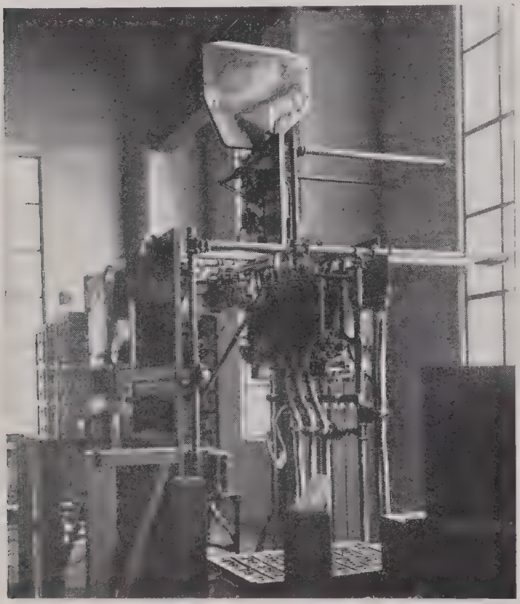

Fig. 7. Relay and Instrument Panels with High-speed Circuit Breaker, Converter Field Rheostat, Direct-current Contactors, Low-speed Breaker, and Load-limiting Resistors. Equipment for 1000-kw. Synchronous Converter Unit

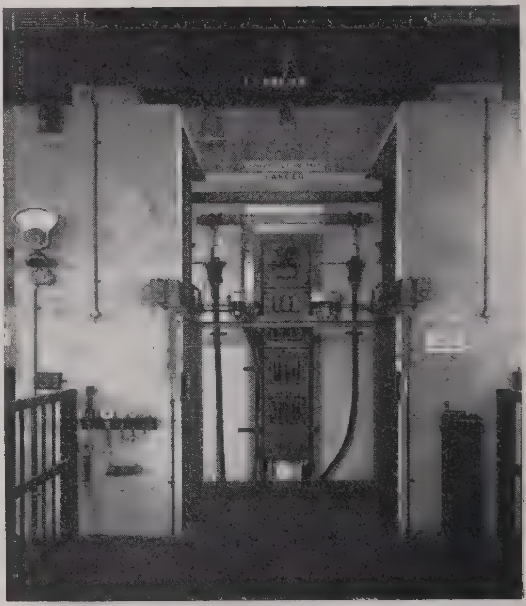

Fig. 8. 20,000-volt Cubicles of Double-unit Substation. Between the cubicles are the direct-current busbars and double-unit panels carrying the equalizer contactor, master starting elements, and time-delay relays for both machines. The controller on the right is for giving priority of starting to either converter

TABLE I

DATA ON THE OPERATION OF THE AUTOMATIC SUBSTATIONS

Substations and Units	Date Substation went into commission in year 1923	Service	Operations	Machine hours	Hand reset shutdowns	Percent failures
Springvale A Springvale B	July 18 Dec. 5	Outer Suburban	3450	11250	17	0.49
Mitcham A Mitcham B	Aug. 16 Apr. 24	Outer Suburban	1812	10567	8	0.27
Reservoir A Reservoir B	Oct. 1 June 21	Inner Suburban	1678	10595	13	0.77
Rosanna	Apr. 14	Inner Suburban	1250	12930	2	0.16
Greensborough	July 6	Country	5665	4222	5	0.09
Total			13855	49592	42	0.356

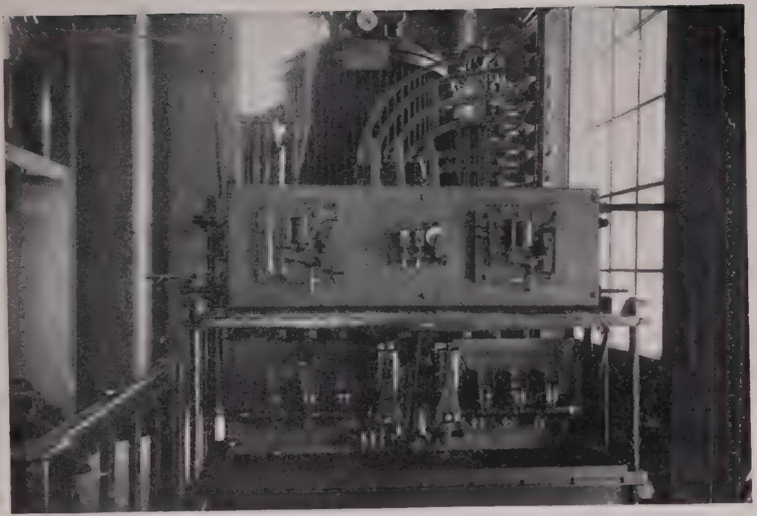

Fig. 9. Starting and Running Contactors for a 1000-kw. Automatic Unit, with Oil Tank Lowered for Inspection

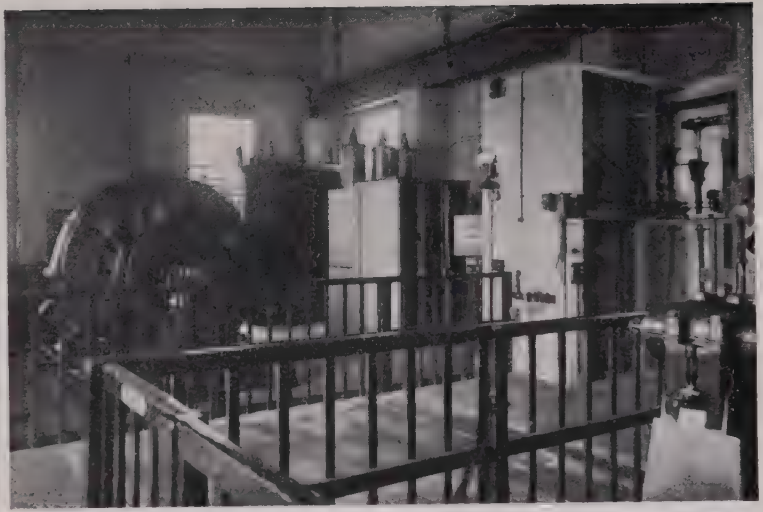

Fig. 10. Interior of the Reservoir Substation Equipped with Two 1000-kw., 1500-volt Converters, Showing One Converter, Transformer, and Oil-circuit Breaker. The pit in the center is to receive the transformer when removing its core

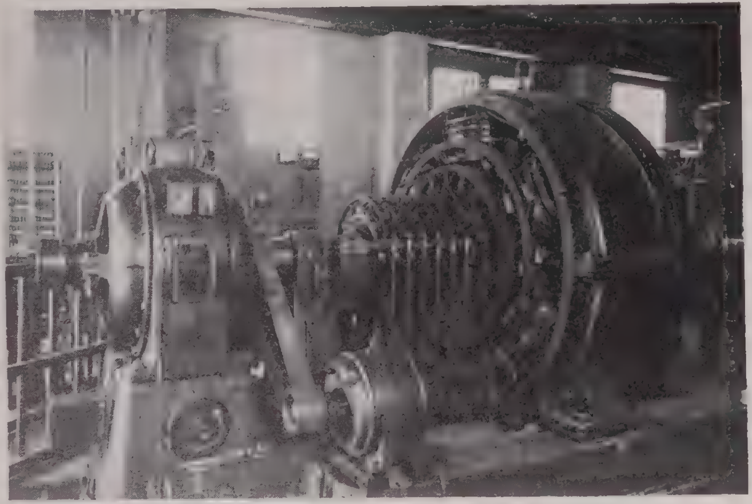

Fig. 11. The Alternating-current End of One of the 1000-kw. Synchronous Converters and the Direct-connected Starting Motor and Exciter

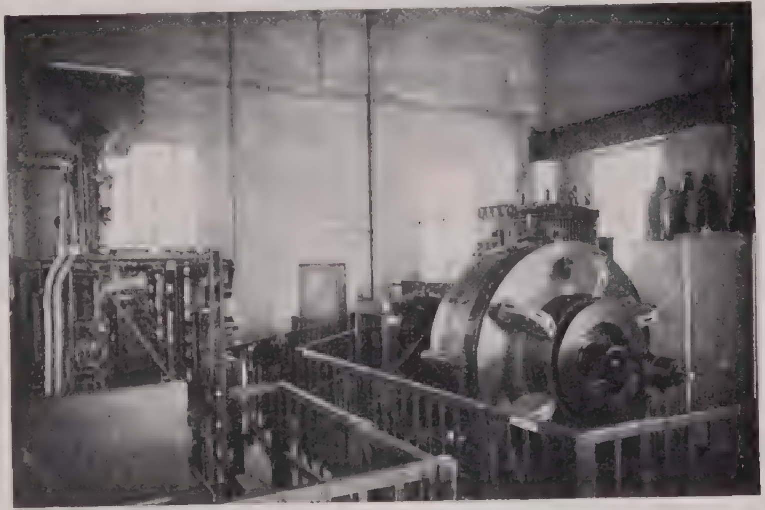

Fig. 12. General View of the Interior of a Double-unit Substation, Showing a 1000-kw. Synchronous Converter, Transformer, and Automatic Control Equipment

matic substation in general costs considerably less than the manual one on account of the smaller and cheaper buildings required. Under local conditions, stations such as these would require three shifts per day with one man per shift. The wages bill would be $4905 per annum (at $4.80 to the pound sterling) for each station or $3066 per annum per 1000-kw. of plant installed.

The maintenance and supervision charges are not more than those for manual stations. In this system the stations are divided into groups, each group being under an inspecting engineer who is responsible to the distribution engineer for the operation and maintenance of the stations under his charge. The five automatic stations together with four manual ones form a group.

Fifty-five per cent of the inspecting engineer's time and 60 per cent of his assistant's time is charged to the five automatic substations. This works out at $2232 per annum or $279 per annum per 1000 kw. of installed capacity. Maintenance on the automatic stations is carried out by two men, a mechanic and his assistant, who visit the stations in turn. At each visit one unit is attended to. The converter is blown out with compressed air, the brushes are examined and cleaned, and all devices are inspected and if necessary are adjusted. The results of this inspection are logged by the man doing the work and from his reports the operation and maintenance charts (which will be referred to again) are compiled. These visits are not made on Saturday or Sunday, thus each substation is visited once in seven days and each unit attended to once in fourteen days except in the case of the two single-unit stations in which the unit receives attention at each visit.

The amount chargeable for this work is at present the whole time of these two men, but it is expected that they will also be able to look after the new substations when they are in operation. The present charges are $2720 per annum or $340 per annum per 1000 kw. installed. The total of these charges is roughly $620 per annum per 1000 kw. installed capacity. To this should be added the repairs to instruments and plant, due to breakages, etc., but a reliable figure for this cannot be given until the stations have been in service some years.

Records

In the distribution engineer's office, records are kept of inspections, maintenance, operations, shut-downs, etc. Besides being kept in detail they are plotted on wall charts.

Details of Equipment

The whole of the switch gear in the automatic equipment was supplied by the General Electric Company. The synchronous converters were manufactured by the British Thomson-Houston Co. at Rugby and as they are of somewhat novel design a description of their leading features may be of interest. The departure from standard design has been brought about by the efforts of the designers to minimize the damage caused by flashing over. In order to prevent as far as possible the flashing of the commutator or brush gear to the frame or pedestal, the armature is carried high above the bedplate.

The commutator has the same diameter as the armature. Clamped on the armature just at the back of the commutator is a multiblade fan which may be seen by reference to Fig. 10. The object of this fan is to cause a strong blast of air across the face of the commutator while it is running. Any arcing which takes place between brush arms of opposite polarity is therefore blown away from the working face of the commutator. Each brush-holder is also provided with a blowout coil, the flux from which assists the blast in driving the arc towards the end of the commutator. The ends of the commutator segments are extended and slotted out, thus forming a series of fingers at the end of the commutator.

The brushes are contained within a brass box which completely protects the flexibles and springs. At the same time the brushes are readily accessible by opening a hinged door in the box. Experience has shown that when flashover occurs all arcing takes place between the end of the surrounding box and the extended commutator tips, and the face of the commutator remains unaffected.

Auxiliary Plant

As has been mentioned, in addition to the synchronous converters and automatic equipment there is a certain amount of auxiliary plant installed in an annex behind the main building.

This equipment consists of a 20,000-volt iron-clad switch panel and a transformer having a secondary voltage of 440 for auxiliary and local services. There is also an air compressor for blowing out the converters. Telephones are located here and also stores necessary for the use of the inspecting staff.

The Development of Low Starting Current Induction Motors

By P. L. Alger

Alternating Current Engineering Department, General Electric Company

No field of electrical engineering has received greater technical attention than that of the electric motor. The possible applications for rotary power are legion and the motor is fast becoming adaptable to them all. The well-nigh universal use of alternating current has brought with it a need for many improvements in induction motor design, since several of the applications require starting and running characteristics not inherent in this motor in its ordinary form. Mr. Alger's article traces the progress of the alternating-current motor toward the goal of low starting current and high torque, and describes some of the latest developments in double-squirrel-cage machines.—Editor.

The Opportunity

The induction motor industry at the present time has new business of approximately $40,000,000 a year. About a million fractional horsepower single-phase induction motors and perhaps 200,000 integral horsepower machines are made annually. The applications cover an extremely wide range, from the washing-machine motor of 1/6 h.p. to the motors driving large warships rated at more than 20,000 h.p. each. The bulk of the business, however, consists of motors built to operate small machine tools, pumps, and similar applications in power stations and manufacturing plants. With this amount and diversity of business, it is natural that many different types of induction motors should be built. It is the object of this article to describe the development of some of the latest of these types—motors intended for full voltage starting with simple automatic control.

An induction motor operates as the result of the production of a revolving magnetic field by alternating currents flowing in the stator winding, and the creation of torque between this field and the alternating currents induced by it in the rotor winding. In starting, the torque produced is zero if the rotor impedance is purely reactive. For, in this case, the induced currents are displaced in space phase with respect to the revolving field in such a way that the maximum current occurs at a point of zero flux and the maximum flux at a point of zero current. Thus, in order to obtain any starting torque, the rotor must have resistance in its circuits, and the more resistance the better, within reasonable limits. On the other hand, when the motor is running, the flux cuts the rotor conductors at a very low frequency, the reactance of the rotor becomes small in comparison with its apparent resistance, and so a high resistance is not needed for satisfactory torque production. Also, the presence of resistance under running conditions involves the occurrence of rotor copper losses, with consequent heating and impairment of the efficiency.

From this it is clear that the starting and running requirements of the motor with respect to the presence of resistance in the rotor circuits are diametrically opposite. The obvious thing to do, then, is to place resistance in the rotor circuits during starting and remove it when the rotor attains full speed; and the obvious way to do this is to provide the rotor with an insulated winding and slip-rings to which external rheostats can be connected.

However, if one can get along with the same winding and connections during starting and running, the motor will not need to have insulation or slip-rings, and so a great saving in cost may be made. A slip-ring motor costs anywhere from 25 to 100 per cent more than a standard-squirrel cage motor, providing a strong economic urge toward the development of a compromise form of motor.

This situation has created a perpetual struggle between the squirrel-cage motor, which is cheap, rugged, and of long life; and the slip-ring motor, which has ideal starting characteristics. On the one hand, attempts have been made to simplify and cheapen the control of the wound-rotor motor; and on the other hand, attempts have been made to improve the starting characteristics of the squirrel-cage motor. The objective of the former is to incorporate the rheostats in the rotor structure with automatically operated cutouts, and the objective of the latter is to design a squirrel-cage winding that will vary its impedance as a result of the variations of motor speed. For the past 30 years, inventors have been busy with these problems, and a multitude of varieties of motor has resulted from their efforts.

Wound-rotor Motors

There are two classes of wound-rotor motor schemes; the use of special winding connections to give internal copper losses during starting, and the consolidation of external rheostats within the rotor structure. The most noteworthy type of motor of the first class is that first described by Gorges.(1) In this motor the rotor winding is arranged with two or more unequal parallel circuits per phase. In starting, the slip-rings are open, but the unequal numbers of turns in the parallel circuits cause circulating currents to flow within each phase. Due to the ineffectiveness of such currents as compared with the currents in a normally arranged winding, the rotor is thus given a high impedance during starting. When the motor attains full speed, the slip-rings are short-circuited so that the currents can re-distribute themselves in a normal way. The art of designing such a motor consists in so arranging the unequal parallel circuits that the effective resistance of the winding is increased more than the reactance. If the reactance only were increased, the starting torque would be unsatisfactory. On the other hand, if the resistance only were increased, the slip at full load torque would be so great as to give an undesirably high rush of current when the slip-rings were short circuited. In general, for each particular application a certain amount of increase in both the resistance and the reactance is desirable. By using more than two circuits in parallel, or by using groups of circuits, the effect of more than one resistance step in starting can be obtained, but, in general, the use of more than one step requires very complicated connections.

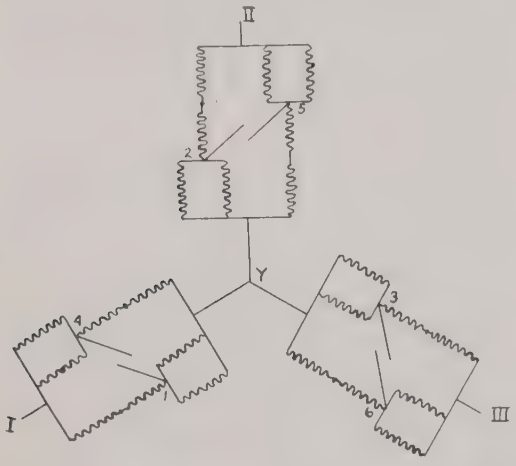

Fig. 1. Winding Diagram for Rotor of the Gorges Motor

Mr. C. Macmillan has studied this type of motor carefully and has devised arrangements of the winding with four bars per slot which give a large increase in resistance with a very small increase in reactance, whereas the original Gorges motor gave a rather large increase in reactance at the same time that the resistance was increased. Thus, the possibilities in design of such motors are fairly extensive and it will be practicable to build machines of this kind at any time that a demand for them shall arise. However, the disadvantages of the occurrence of excessive heating inside the insulation, with consequent danger of voltage breakdown, and of at least as high a cost as the slip-ring motor, have so far precluded their development.

A number of types of slip-ring motor with external rheostats placed on the rotor has been developed. In an old form of General Electric motor, a resistance was placed inside the rotor concentric with the shaft. By pushing in an operating handle inside the hollow shaft, the resistance could be varied at will. In the Zani(2) motor a set of resistances are permanently connected across the windings within the rotor, and in parallel with them there is placed a set of inductance coils. At starting, the current flows through the resistances, but when the motor attains full speed, the current flows through the low resistance inductance coils. In order to avoid having a high inductance of the motor under

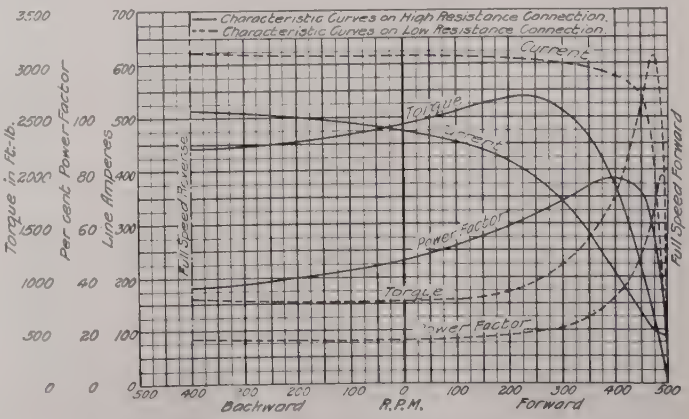

Fig. 2. Characteristic Curves of an Improved Gorges Motor

operating conditions, the iron cores of the inductance coils are thrown out by centrifugal force when the motor attains full speed.

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(1) Hobart, "Electric Motors," Vol. II, pp. 31–36.
(2) Hobart, "Electric Motors," Vol. II, pp. 61–67.

Another variety of motor recently used on a considerable scale has been the carbon-pile motor. Here the slip-rings are connected through piles of carbon discs which interpose a high resistance at starting. As the motor speeds up, the carbon piles are compressed by weights acting under centrifugal force and so their resistances are decreased. Thus, the rotor resistance is automatically changed with the speed, and a smooth torque curve of a desirable shape is obtained. More recently, a new form of General Electric motor has been developed. In this machine the slip-rings are short-circuited by high-resistance non-inductive coils, compactly arranged in the space normally occupied by the slip-rings. As the motor speeds up, these resistances are successively short circuited in two steps by contacts operated by centrifugal force. All these types of motor present considerable engineering difficulties and they all are handicapped by the high first cost of the slip-ring motor. Despite these handicaps, however, they do provide a means of securing very high starting torque per ampere and full automatic control, so that there is a certain demand for them.

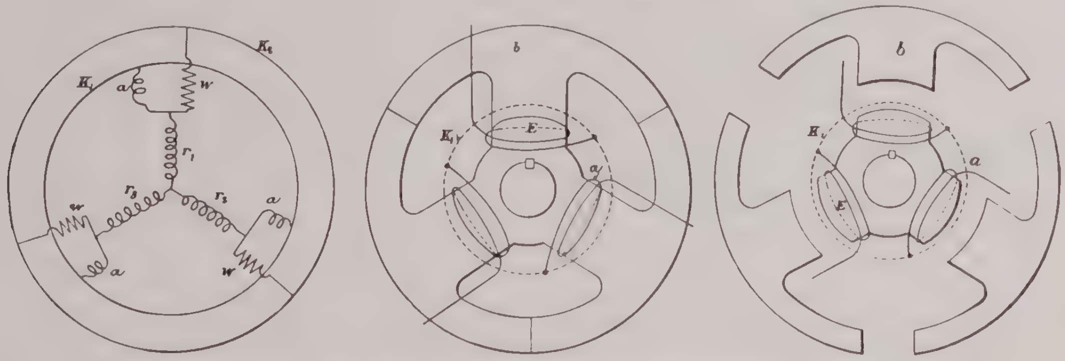

Fig. 3. Arrangement of Zani Motor Rotor with Inductance Coils for Limiting Starting Current(3)

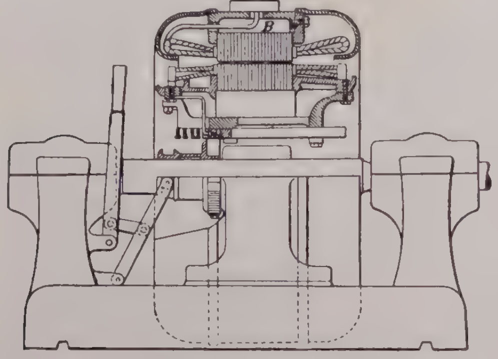

Fig. 4. Round-rotor Motor with Rheostats on Rotor

Intermediate Types of Motor

Several types of motor intermediate between the squirrel-cage and the slip-ring type have been built, of which the Punga(4) motor is one of the most notable. In this motor there is provided a squirrel-cage winding arranged in a few slots underneath a slip-ring winding of twice as many slots. At starting, the slip-ring winding is open-circuited and all the current flows in the squirrel cage. The squirrel cage has both a high reactance and a high resistance so that a desirable compromise between too high a starting current and too low a starting torque is obtained. When the motor attains full speed, the slip-ring winding is short-circuited and the motor then operates in a normal manner. Here, the difficulty is to so design the squirrel-cage winding as to obtain satisfactory starting up to full speed. Usually the speed attained at full load torque is still so low that a high current rush is obtained when the slip-ring winding is short circuited.

A few kinds of squirrel-cage motors have been devised which operate by control of the primary winding rather than by secondary control. A typical example of this type of machine is one due to Boucherot(5) in which two complete stators are provided with a common shaft and frame. Squirrel-cage bars are provided on the rotor, which pass through the slots of both machines, and are short circuited by low-resistance end rings on their outside ends. A third high-resistance end ring is provided between the two rotors.

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(3) Figs. 3, 4, 5, 6 and 7 of this article are reproduced from "Electric Motors," by H. M. Hobart.

(4) Hobart, "Electric Motors," Vol. II, pp. 304–306.

(5) Hobart, "Electric Motors," Vol. II, pp. 42–44.

At starting, one of the stators is revolved with respect to the other into such a position that the voltages induced by it in the rotor bars are out of phase with those induced by the other stator. Thus, the induced rotor currents are held to a low value at starting, even though full voltage is impressed on the stators. As the motor speeds up, the movable stator is gradually shifted until its voltages are in space phase with those of the second stator. The motor then operates as a normal squirrel-cage machine.

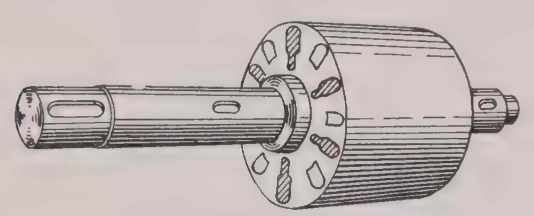
Fig. 5. Rotor of Punga Motor

It will be seen that all the motors so far described have had costs not less than that of a plain slip-ring motor, so that the only advantages gained have been simplicity of control and a saving in space.

Squirrel-cage Motors with Mechanical Control

Coming now to the squirrel-cage types of machine, there are two general classes, those depending upon the mechanical effects of centrifugal force and those depending upon the variation of frequency in the rotor bars. There are two principal types of the first class, which depend, respectively, on modification of the end rings, and of the squirrel-cage bars.

The Morelli[6] motor is a plain squirrel-cage motor except that it is provided with a special end ring construction on one end. On this end, a high-resistance ring is provided so that high starting torque is obtained with low current. Attached to the inside of this ring in one or more places are circular arcs of heavy copper. At the motor speeds up, these copper arcs are gradually thrown out by centrifugal force and pressed against the inside of the high resistance ring. The contact pressure obtained by this means is great enough to enable the current to flow through the low-resistance path so provided and thus the motor operates as a normal low-resistance squirrel-cage machine. The principal disadvantage of this motor, aside from its obvious mechanical difficulties, is the fact that the heating due to the resistance losses occurs in the end ring, which is exposed to the air. Consequently, the temperature rise of the end ring during starting may be very large and there is danger of burn out if the time of starting is unduly prolonged.

An example of the second type is a normal squirrel-cage rotor provided with specially deep slots, the bars being placed in the bottoms of the slots. The middle portions of the slots are made narrower than the top or the bottom and the narrow spaces resulting are occupied by movable steel bars, held down against the squirrel-cage bars proper by springs. At starting, the leakage flux due to the rotor currents passing across these movable steel bars gives high reactance and high eddy current losses, thus giving a satisfactory torque and starting current. As the motor accelerates, the steel bars move out against the springs into the relatively wide upper portions of the slots, thus decreasing the reactance of the machine. Here again, the mechanical difficulties of design are considerable. Also, the limited space available both in width and in depth requires that a considerable portion of the reactance interposed at starting should still remain during operation, and so the operating characteristics of the motor are not as good as those of a standard squirrel-cage machine.

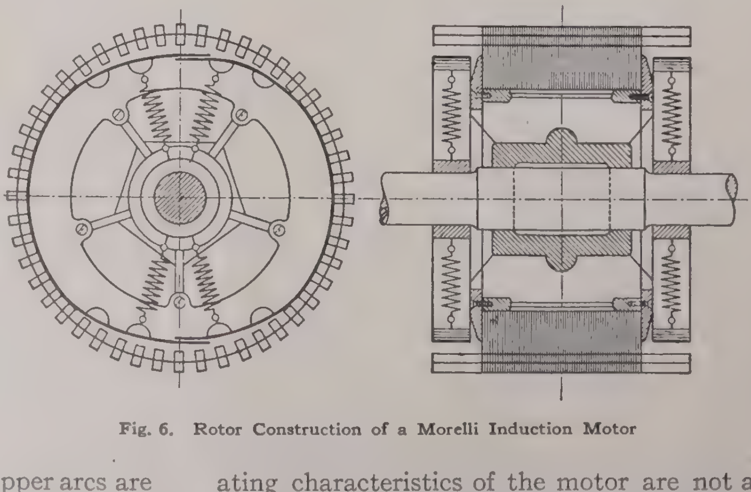
Fig. 6. Rotor Construction of a Morelli Induction Motor

The most fertile field of all for the inventor has been the development of squirrel-cage motors that depend upon the variation of rotor frequency as the motor speeds up to obtain a difference between the starting and running constants of the motor. As all machines in this class operate by virtue of the so called skin effect, and as this phenomenon obeys definite mathematical laws which must be taken into account if satisfactory results are to be secured, it will be desirable to study the theory of the subject before considering motors of this type in detail.

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[6] Hobart, "Electric Motors," Vol. II, pp. 307–308.

The theory of motors utilizing the skin effect may be divided into two parts, the first part dealing with the calculation of the effective impedances of bars of particular shapes, and the second part dealing with the determination of the most favorable proportions of bars of a given form for use in a given motor. We will deal with the first part of the theory in the following paragraphs, and later with the second part.

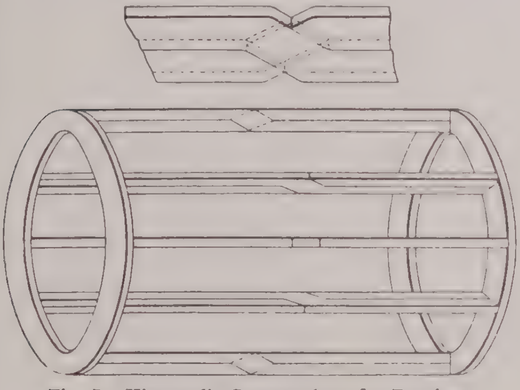

Fig. 7. Kierstead's Construction of a Two-bar Deep Squirrel Cage

Deep Bar Effect

If a rectangular bar of depth d is placed in an open slot of the same width as the bar, and a current of frequency f is passed through the bar, the leakage flux crossing the bar will produce a distortion of the current distribution. This distortion will be greater the higher the frequency. The solution of the problem of calculating the effective resistance and reactance of such a bar is well-known. The results are, that if K is the ratio of the effective to the d-c. resistance and J the ratio of the effective to the d-c. inductance of the bar

$$K = 1 + \frac{4}{45}(\alpha d)^4 + \ldots\ldots \text{ if } \alpha d < 1.2$$

$$K = \alpha d \ldots\ldots\ldots\ldots \text{ if } \alpha d > 4 \text{ and}$$

$$J = 1 - \frac{8}{315}(\alpha d)^4 + \ldots\ldots \text{ if } \alpha d < 1.2$$

$$J = \frac{3}{2\alpha d} \ldots\ldots\ldots\ldots \text{ if } \alpha d > 4.$$

In the foregoing equations, α is the so-called eddy current constant, which is proportional to the square root of the frequency and the inverse square root of the resistivity. It is equal to 2.71 for copper at 75 deg. C. and 60 cycles, if d is expressed in inches.

A brief study of these formulas as applied to actual squirrel-cage bars shows that in order to obtain any reasonable value of K at 60 cycles a very narrow and deep bar is required. Furthermore, if such a bar is used, the lower part of it will carry practically no current in starting, and as a result of this the effective reactance at starting will be much lower than at full speed. Consequently, a plain rectangular bar gives an unsatisfactory mechanical construction, and comparatively poor electrical characteristics. Therefore, the use of such a bar is undesirable.

One of the first ideas which may occur to one endeavoring to avoid these difficulties is to divide the deep bar into two or more vertical portions and to place these portions in series. By this means, the current can be forced to flow through the lower portion of the conductors during starting, thus avoiding an undesirably low value of starting reactance. This idea was developed by Kierstead.(7) However, careful consideration of this scheme shows that it too is mechanically unsatisfactory and that desirable 60-cycle electrical characteristics can be obtained from it only when the depth of conductor exceeds about 2 inches. Such a depth is very rarely attained in induction motors.

The next idea that may be considered is that of turning the lower, comparatively useless, part of a deep rectangular bar upwards, thus obtaining an L-shaped bar. The L-bar has been studied very carefully and it has been found that by its use better mechanical and better electrical characteristics can be obtained than with either of the constructions described above. The theory of the calculation of the a-c. impedance of an L-bar is rather elaborate. The work may be carried out by straightforward methods similar to those used by Field, Rusch and other writers, but it may be more elegantly performed by the vector methods developed by Professor W. V. Lyon.(8) The accompanying charts (Figs. 9 and 10) show the values of $\frac{R_{a\text{-}c.}}{R_{d\text{-}c.}}$ for L-shaped bars of different proportions and of different depths. The approximately horizontal curves marked *2*, *3*, *4*, etc., on these charts are the loci of a series of differently shaped bars having the same values of d-c.

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(7) Hobart, "Electric Motors," Vol. II, pp. 291–303.
(8) *Trans. A.I.E.E.*, Vol. XL, 1921, pp. 1361–1409.

resistance and inductance. The peaks of these curves locate the L-bars that are so proportioned as to give the maximum possible ratio of effective to d-c. resistance at starting, with given running characteristics.

It is evident from inspection of the charts that the improvement of the L-bar over the plain bar, in per cent, is greater the greater the depth of the plain bar. However, for values of αd below 2.5, corresponding at 60 cycles to a rectangular bar less than an inch deep, the L-bar is slightly inferior to the plain bar in electrical characteristics. For such low values of αd, neither construction is satisfactory.

The theory of eddy currents in conductors shows that as the frequency increases the ratio of the resistance to the reactance of the conductor approaches unity as a limit. Although the power-factor of the conductor does oscillate to and fro across the 0.707-line as the frequency or depth is increased, the maximum value of power-factor that can be attained is hardly more than 0.72 in any case. It is, therefore, clear that the practical limit attainable in starting resistance by any deep-bar scheme is a value of resistance equal to the starting reactance of the bar itself.

While a few motors have been made using the L-bar arrangement, the possibilities in this direction do not seem as great as for schemes using double squirrel cages. This is true for the reasons that a double-squirrel-cage winding can be made to give a starting power-factor considerably greater than 0.707, and that such a winding permits a more satisfactory mechanical construction than the L-bar type does. The philosophy of this conclusion may be seen from the fact that by going from the simple bar to the L-bar an improvement was made and that this improvement was due to "lumping" the electrical constants of the bar. Evidently by carrying this "lumping" still further, so as to concentrate nearly all the resistance of the bar at the top, nearly all the conductance at the bottom, and nearly all the reactance between the two, a still further gain can be obtained.

A further advantage of the double squirrel cage is that it enables the entire rotor winding, end rings and all, to participate in the variation of impedance with frequency, if this is desired. Where small motors are involved, the inherently high resistance of the end rings and of the portions of the bars projecting beyond the rotor punchings, in neither of which do true eddy currents occur, requires that very high values of K be secured in the bars themselves if a plain deep bar motor is to have a reasonably high ratio of total secondary starting to running resistance. With double-squirrel-cage motors, smaller resistance ratios may be used, as the ratio applies to a larger proportion of the total secondary resistance.

Theory of the Double Squirrel Cage

In the double-squirrel-cage motor, a secondary winding of relatively high resistance and low inductance is placed electrically in parallel with a winding of relatively high inductance and low resistance. In starting, the reactance of the latter squirrel cage is high and so the current flows chiefly through the high-resistance winding. At full speed, the reactance is low, and the current flows chiefly through the low-resistance winding. The equivalent circuit of such a motor is the same as that of a normal squirrel-cage motor, except for the addition of an extra circuit in parallel with the ordinary secondary circuit. Assuming a given primary, there are thus four arbitrary constants which can be varied to obtain the best design. These four constants are:

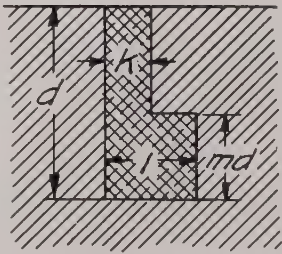

Fig. 8. L-bar Surrounded by Magnetic Material

m = ratio of height of foot to total height.
k = ratio of width at top to width at bottom.

R_A = resistance of lower squirrel cage;
X_A = reactance of lower squirrel cage, less mutual reactance with upper squirrel cage;
X_B = reactance of upper squirrel cage, less mutual reactance with lower squirrel cage;
R_B = resistance of upper squirrel cage.

In addition to these constants, a fifth constant, k, may be assumed, equal to the ratio of effective to d-c. resistance of the lower squirrel cage. By including k in the equations the effect of eddy currents in the lower squirrel cage may be determined, and thus the possible gain due to the use of three or more squirrel cages in place of two may be determined.

It is difficult to establish a criterion by which to judge the relative excellences of different squirrel cages, especially when it is permissible to modify the primary as well as the secondary windings. However, for the usual general purpose motor, and with a fixed primary, a fairly satisfactory criterion is the value of the secondary resistance at starting. That squirrel cage is the best, electrically speaking, which has the highest starting resistance, with fixed values of running resistance and reactance. This criterion gives two equations that can be used to eliminate two of the five arbitrary constants involved in the expression for secondary resistance.

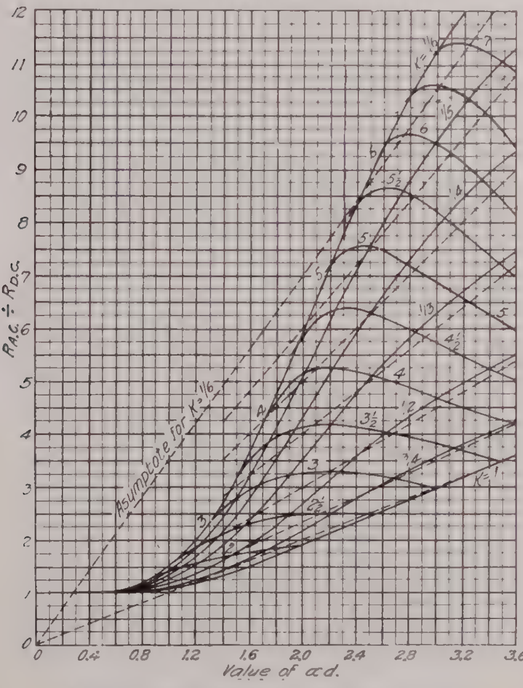

Fig. 9. Resistance Ratio for L-bars, $m=1/2$

Thus, two assumptions must be made in regard to the squirrel-cage design before a solution can be found. Depending on what these assumptions are, the solutions may be divided into four principal cases.

Case I: $X_B=0$, $k=1$.

Upper and lower bars in the same slots. Both bars very shallow, so that no appreciable eddy currents occur in them, and the resistance due to flux crossing the top bar is negligible.

Case II: $X_B=0$, $k>1$.

Similar to Case I, but reactive flux of lower bar produces eddy currents in conducting material interposed in the selective air gap between squirrel cages, or in the lower bar itself.

Case III: $X_B>0$, $k=1$.

Upper and lower squirrel-cage bars arranged in separate slots. Both bars free from eddy currents. This also covers the case of bars arranged in the same slots, when the reactance due to flux crossing the upper bar must be taken into account.

Case IV: $X_B>0$, $k>1$

Upper and lower squirrel-cage bars in the same slots. Upper bars relatively thin and deep, so that eddy currents occur in them due both to their own currents and the currents in the lower bars. This is practically the same as the L-bar in theory.

The solution of Case I is easily obtained from that of Case II by making $k=0$ in the resulting expressions. To solve Case II, it is most convenient to express the starting resistance of the two squirrel cages in parallel in terms of the constants R_A, X_A, R_B, and k, to substitute for R_B and X_A their values in terms of the running constants of the motor, and then to differentiate the starting resistance with respect to R_A and equate the result to zero. The value of R_A so determined is the best possible value under the given conditions.

Calling R_O and X_O the values of running resistance and reactance which may be tolerated without too seriously reducing the maximum output, power-factor, and efficiency of the motor, and substituting these values in the expression for the starting resistance of the double-squirrel-cage motor, in place of their equivalent values in terms of R_A, etc., the expression for the starting resistance of the motor becomes:

$$R_f=\frac{R_O R_A\left[kR_0^5+(R_A-R_O)\ (k^2R_0^4+R_A^2X_0^2)\right]}{R_0^4\left[k\ (R_A-R_0)+R_0\right]^2+(R_A-R_0)^2\ R_A^2\ X_0^2}$$

Differentiating this equation with respect to R_A and equating to zero, a fourth-degree equation in R_A is obtained. Solving this equation by approximate methods, we get;

$$\frac{R_A}{R_O}=\left(\frac{R_O+X_O}{X_O}\right)$$

$$-\frac{(k-1)R_0^5+2R_AX_OR_0^3-X_0^2R_O(R_A-R_O)^2}{2R_A^2\ X_0^3}+\dots$$

Substituting this value in the expression for R_f, the maximum value of R_f is found to be:

$$R_{f\ \text{max.}}=R_O+\frac{X_O}{2}+\frac{R_OX_O\,(k-1)^2}{2\,(X_O+R_O)^2}+\ldots\ldots\ldots$$

Inspection of this equation indicates that a slight gain can be made by making k greater than unity. However, as the coefficient of $(k-1)$ is small, and as making k greater than unity involves a reduction of X_A at starting, which has been neglected in this theory, any such gain is small. From a general point of view, since making k greater than one corresponds to distributing instead of "lumping" the constants of the winding, it would appear that such a step is in the wrong direction. Therefore, and because of the increased mechanical difficulties that are met, it may be stated as a general rule that there is no net advantage in building a triple squirrel cage or in using a deep lower conductor in a double squirrel cage, as compared with building a plain double squirrel cage.

Making k equal to unity in these equations, the solution for Case I is obtained—corresponding to the simplest and most generally used form of double squirrel cage. The best values of the three arbitrary constants, R_A, X_A, and R_B for this case are then as follows:

$$R_A=R_O+\frac{R_0^2}{X_O}$$

$$X_A=\frac{(R_O+X_O)^2}{X_O}$$

$$R_B=R_O+X_O$$

When the two squirrel cages are designed to have these constants, they will have a combined starting impedance equal to $\left(R_O+\frac{X_O}{2}\right)+j\frac{X_O}{2}$ and a combined running impedance, referred to primary, equal to R_0+jX_0, than which no better characteristics are obtainable on the basis of the assumed conditions and the assumed criterion of excellence.

A brief consideration of Case III in the light of the Case I results shows that III is not so good as I. For, if in a given double squirrel cage of type I any portion of the total running reactance is taken away from the bottom squirrel cage and put into reactance flux crossing the top bars, then this part of the flux becomes ineffective in forcing current through the high-resistance bars at starting. As a general rule, for every unit of upper-bar reactance there must exist as large a unit or larger of mutual reactance between the two squirrel cages, so that when X_B is obtained (by subtraction of the mutual from the top-bar reactance) it is found to be negative. Even though the condensive reactance of B does throw the A and B currents more out of phase, this effect does not compensate for the reduction of X_A that is required to hold the same value of X_0.

Thus, it is a general rule that X_B, the reactance due to flux crossing the upper bars (or the zigzag leakage around bars placed in separate slots) should be made as small as possible. In Case IV part of the loss due to X_B being large is made up for by the eddy currents it produces in the top bars, but this case, too, is slightly inferior to Cases I and II.

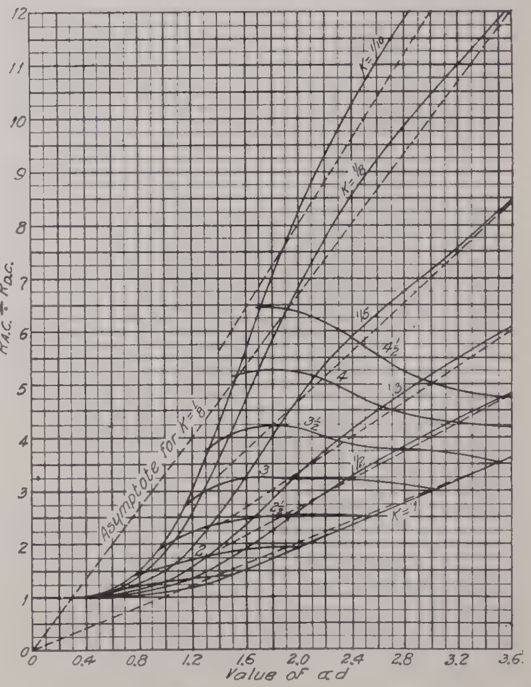

Fig. 10. Resistance Ratio for L-bars, $m=1/3$

As all of the increase in starting resistance obtainable by the skin effect is the direct result of the presence of the secondary reactance, it is generally true that the obtainable increase in resistance is directly proportional to the secondary bar reactance. From these facts there follows the important conclusion:

> If it is desired to increase the starting resistance of a squirrel-cage motor above its running value by an amount ΔR, by

means of the variation in secondary frequency during starting, then it is necessary to add at least an amount 2 ΔR to the running reactance of the motor, and half of this additional reactance will be present at starting.

With this principle in mind, it is easy to determine the possibilities of improving the starting of any given motor without unduly impairing its running power-factor and its breakdown torque. Generally speaking, any ordinary polyphase squirrel-cage induction motor can be so modified by the addition of a double-squirrel-cage winding as to reduce its starting current to about 450 per cent and raise its starting torque to 250 per cent of full load values on full voltage; as compared with normal values of 700 and 175 per cent. This improvement in starting characteristics is made with an average sacrifice of 4 per cent in full-load power-factor and 1 per cent in efficiency; and is accompanied by a reduction in the breakdown torque, roughly from 275 to 200 per cent.

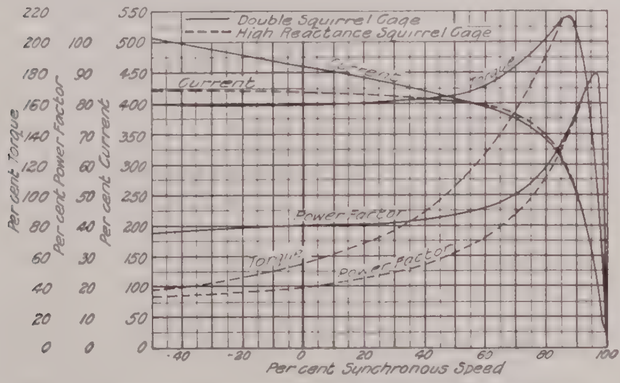

Fig. 11. Starting Characteristics of the Double Squirrel Cage Compared with Those of the High-resistance Squirrel Cage

On the basis of a double-squirrel-cage design proportioned as above outlined, so as to secure the maximum possible starting resistance consistent with given running characteristics, an ideal speed-torque curve may be calculated by taking the squirrel-cage resistance referred to primary at any slip s as:

$$R_S = \frac{R_O}{s} + \frac{s\,X_O}{1+s^2}, \text{ and}$$

its reactance referred to primary as:

$$X_S = \frac{X_O}{1+s^2}$$

instead of the conventional values R_0/s and X_0, respectively. Comparative starting characteristics for a motor of this type and a normal squirrel-cage motor of the same running characteristics are shown in Fig. 11.

It is clear from the foregoing that the plain double-squirrel-cage motor is the best of all the types of squirrel-cage motor that have been considered, from the point of view of obtaining a high starting torque per ampere at the same time that satisfactory running characteristics are secured. However, there are so many varieties of motor application, each requiring particular starting and running characteristics, that there is a demand for motors having simply a low starting current with good running characteristics as well as for motors having a high starting torque per ampere with good running characteristics.

When the former type of motor is designed, the value of starting torque becomes unimportant, as long as at least 75 per cent of full load torque is obtained on full voltage. In this case, therefore, there is desired a motor with high reactance and with only a slight increase in the starting resistance above the value of running resistance. To meet this demand, it has been found desirable to develop a plain squirrel-cage motor having idle steel bars placed in the slots above the squirrel-cage bars proper.(9) These idle steel bars can be inserted without much inconvenience or cost.

In starting, the leakage flux of the squirrel-cage winding is high, and in crossing the steel bars it induces eddy currents which increase the effective resistance of the winding. At full speed this leakage flux is no greater than at starting, while its frequency is so low as to reduce the extra losses to a negligible figure. It is necessary to have an air gap between the steel bars and the slot walls in order to avoid saturation at starting, with consequent excessive increase of starting current. By filling this air gap with copper or brass strips, additional eddy currents can be created of a magnitude greater or less depending upon the material employed for the filler. Thus, by choice of materials, the starting resistance can be increased appreciably above the running resistance, while at the same time the eddy currents are not allowed to become large enough to reduce the starting inductance appreciably below the running inductance. By such means, therefore, it is possible to obtain a motor with practically the same reactance, running and starting, yet having a starting resistance considerably greater than its running resistance and a very low starting current.

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(9) U.S. Patent No. 1,508,1 52.

If the starting current of a standard motor were reduced by simply adding series reactance, the starting torque would be too greatly reduced. Thus, this new type of motor meets a definite need which is not filled by any other type of motor.

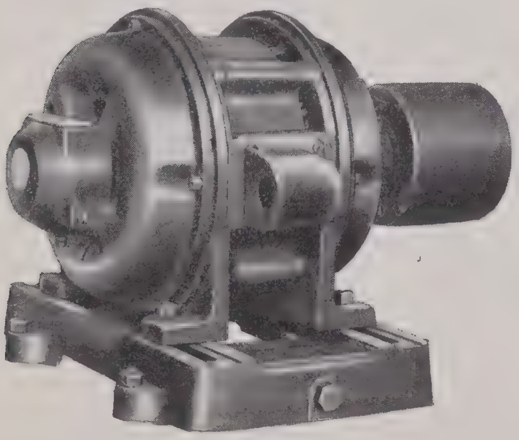


Fig. 12. Standard Type of Double-squirrel-cage Motor

Summary

This review of the various types of low starting current motors that have been made shows that it is quite possible to specify almost any desired shape of torque curve and then to build a motor to give that torque curve with full automatic control and with a lower starting current than that given by the plain squirrel-cage motor. Generally speaking, the starting current can be reduced to about 4½ times full-load current, but any decrease of current below this value is attended by a reduction of the maximum output at full voltage below the 175 per cent specified by the A. I. E. E. rules.

The squirrel-cage varieties of motor which give this low starting current, and either high or low starting torque as may be desired, are filling a definite demand which has arisen in recent years, due to the desire for greater simplicity and lower costs. Such a motor, when starting at full voltage may be cheaper than an ordinary squirrel-cage motor with a compensator, and it is much cheaper than a slip-ring motor with its rheostats. If the amount of power available at the motor terminals is sufficiently great so that the current rush at starting is not objectionable, full voltage starting often proves preferable to the conventional reduced voltage starting. As this condition becomes more common, the demand for the low starting current motor will increase. Ultimately, if this tendency continues, the very high starting currents of the plain squirrel-cage motor may be found tolerable even in large sizes and so the double-squirrel-cage motor may again decline in usefulness. In any case, the direction of advance is away from the slip-ring motor in small sizes and toward the use of an increasing variety of types of squirrel-cage motor.

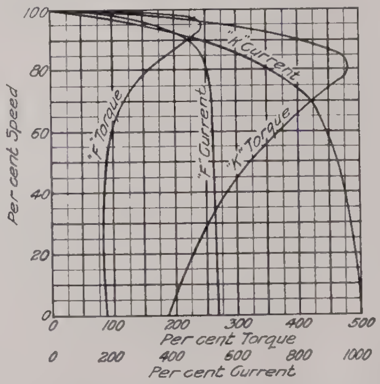


Fig. 13. Starting Characteristics of a Typical Station Auxiliary Motor with Idle Steel Bars

Over-voltage on Transmission Systems Due to Dropping of Load

By E. J. Burnham

Central Station Engineering Department, General Electric Company

To the best of our knowledge, the following article records the first investigation made to determine the extent to which the voltage of a transmission line rises when all or a considerable part of the load is abruptly dropped. The quantitative results obtained exceed those that would naturally be expected, and therefore indicate that the subject is one which should be given more attention because of the abnormal stress which over-voltage places on the insulation. The author presented this report of the tests as a paper at the Annual Convention of the A.I.E.E. at Saratoga, N. Y., June 26, 1925.—Editor.

Much has been written about instantaneous rises of voltage due to surges caused by switching, and transients due to short circuits, but very little has been said regarding the rise of voltage due to dropping of load on an alternating-current system.

Great interest has been shown in various sections of the country during the past year in the voltage obtained when a waterwheel-driven generator, or a hydroelectric station, loses all or a large part of its load, since voltages obtained in this manner are much higher and develop more rapidly than would ordinarily be expected.

When load is lost on an alternating-current generator, or group of alternating-current generators, the manner in which the voltage rises and the time interval taken for such a rise varies according to the following factors:

(1) Voltage regulation and design of the generator.

(2) Type and speed regulation of prime mover connected to generator.

(3) Generator excitation obtained from direct-connected exciter, exciter motor-generator set, or direct-current bus.

(4) Amount and power-factor of load dropped.

(5) Voltage regulators used or not used.

(6) Place in circuit where load is tripped.

(7) Connections including lines, transformers, etc., between generator and load.

(8) Over-voltage or over-speed devices used or not used.

With these points in mind, calculations were made to determine the maximum rise in voltage on ordinary waterwheel-driven generators when load was lost under different conditions. The results of these calculations are shown in Table I. Details regarding the method of making the calculations are given later.

In order to check the calculations and to obtain further information, a series of tests were made at the Spier Falls Station of the Adirondack Power & Light Corp., in which load was dropped in different ways and under many different conditions on an 8500-kv-a., three-phase, 60-cycle, 164-r.p.m., 6600-volt, 80-per cent power-factor waterwheel generator, connected to a large 60-cycle system, through an 18,000-kv-a. bank of transformers and a 40-mile, 66,000-volt transmission line.

TABLE I

VOLTAGE RISE IN PER CENT OF NORMAL VOLTAGE

Type of Prime Mover	Over-speed in Per Cent	Per Cent With Voltage Regulator		Per Cent Without Voltage Regulator	
		With Direct-connected Exciter	Without Direct-connected Exciter	With Direct-connected Exciter	Without Direct-connected Exciter
Water-turbine	25–35	50–80	40–65	90–100	60–85

The connections and arrangement of equipment between the generator and substation are shown in Fig. 1. By use of circuit breakers, *1*, *2*, and *3*, load could be tripped at any one of three different places. These circuit breakers will be referred to as generator, transformer-high-voltage, and substation circuit breakers, respectively.

The generator had a direct-connected exciter, but in order to make tests also with the generator separately excited, a temporary connection was made to a small, waterwheel-driven exciter. However, the limited capacity of this exciter would permit the generator when separately excited to carry only 4000-kw. load at 98 per cent power-factor.

A vibrating type, 60-cycle voltage regulator was in the station, so plans were made to use that in some of the tests.

Connections were made to an oscillograph so that any three of the following waves could be recorded at the same time:

(1) 60-cycle or 40-cycle timing wave.
(2) Generator field or exciter voltage.
(3) Generator current.
(4) Generator voltage.
(5) High-tension voltage at a point between transformer and transformer high-voltage circuit breaker.

Table II gives details regarding tests in which load was dropped in different ways and under different conditions.

It will be noted that 6700 kw. was the largest load dropped. The generator could not carry a greater load than this because of the water conditions at the time the tests were made.

Commercial load was used for the tests; therefore, under these operating conditions, it was not always possible to drop the load most desirable for a particular test. However, by giving consideration to the amount of load dropped, proper comparisons may always be made between the different tests.

It will also be noted that after a load was dropped, in some cases the speed reached 152 per cent of normal, which is a much greater speed increase than generally obtained on waterwheels under similar conditions. This large speed increase is accounted for by the fact that the waterwheel governor had not received final adjustment, but this does not make the tests less valuable, since the speed characteristics for each test can be determined by making a comparison between the timing wave and the generator-voltage wave. Furthermore, the large speed regulation of the waterwheel was offset, to some extent, by the load dropped, which was less than normal; therefore, the results are not far from what might ordinarily be expected, as will be shown later.

Load Dropped by Tripping Generator Breaker

Direct-connected Exciter Used

Fig. 2 shows the results of two tests, a voltage regulator being used in Case 2, but not in Case 1. Curves *1S* and *2S* show the rise in speed that took place as soon as load was dropped. Curves *1V* and *2V* show the corresponding rise in generator voltage.

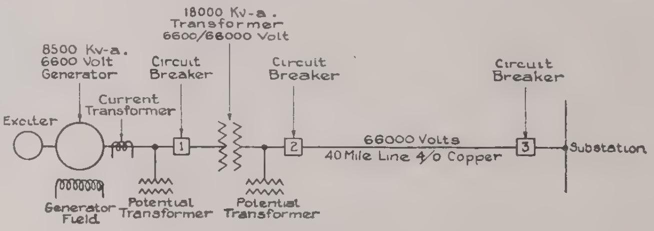


Fig. 1. Arrangement of Equipment for Test

The curves show that as soon as the generator breaker was tripped, the generator voltage rose instantly to approximately 112 per cent of normal, and then increased in accordance with Curve *1V* or *2V*, *1V* being without voltage regulator and *2V* being with voltage regulator. The effectiveness of the voltage regulator is plainly seen when a comparison is made between the curves. The maximum over-speed is greater in Case 2 than in Case 1, as shown by the speed Curves *2S* and *1S*, due to the fact that a slightly larger amount of load was dropped in Case 2 than in Case 1.

TABLE II

Test No.	Load Dropped Kw.	Power-factor Per Cent	Direct-connected Exciter	Regulator	Over-voltage Relay	Over-frequency Relay	Breaker Tripped by Hand	Breaker Tripped by Relay	Maximum Voltage in Per Cent of Normal
1	5900	83	Yes	No	No	No	1	–	195
2	6100	83	Yes	Yes	No	No	1	–	151
3	4000	98	No	No	No	No	1	–	128
4	6500	83	Yes	No	No	No	2	–	174
5	6400	90	Yes	Yes	No	No	2	–	157
6	6400	90	Yes	No	No	No	2	–	185
7	6700	83	Yes	No	No	No	3	–	218
8	6100	87	Yes	Yes	No	No	3	–	168
9	6500	83	Yes	Yes	Yes	No	2	1	113
10	6150	83	Yes	Yes	No	Yes	2	1	126
11	6700	83	Yes	No	Yes	No	3	2	183
12	6700	83	Yes	No	Yes	No	3	1	201
13	3500	70	Yes	No	Yes	Yes	2	1	138
14	6700	83	Yes	Yes	No	No	3	–	206
15	3500	66	Yes	No	Yes	No	2	1	138

Referring to Case 1, Fig. 2, the solid line, *1V*, represents test values as recorded on an oscillogram, while the small circles were plotted from calculations. In Case 2, the solid line *2V* represents test values, while the small triangles are taken from calculations. The method by which the calculations were made will be given later.

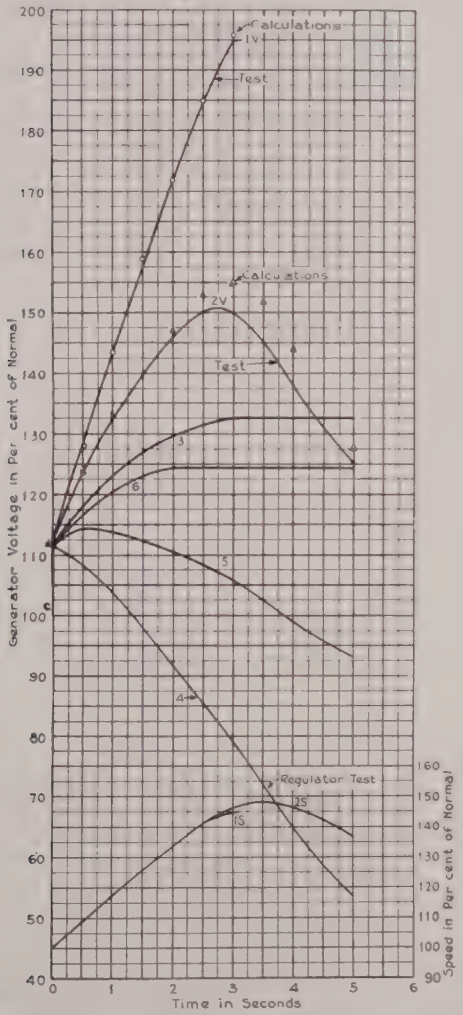


Fig. 2. ***Case 1.*** **5900-kw. Load Dropped by Tripping Generator Breaker. Direct-connected Exciter. No Regulator** ***(Test 1)***

Case 2. **6100-kw. Load Dropped by Tripping Generator Breaker. Direct-connected Exciter. Regulator in Operation** ***(Test 2)***

Generator Separately Excited

The results of a test in which the generator was separately excited are shown in Fig. 3. As only a 4000-kw. load was dropped, the speed did not rise as high as it did in the tests previously described.

After the load was dropped, the voltage increased in accordance with Curve *1V*. The small crosses represent calculated points.

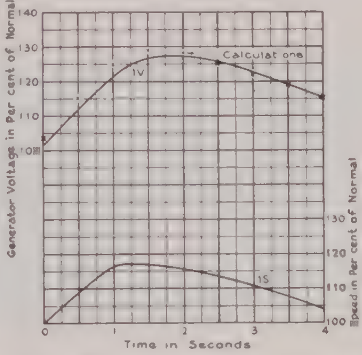


Fig. 3. 4000-kw. Load Dropped by Tripping Generator Breaker. Generator Separately Excited. No Regulator ***(Test 3)***

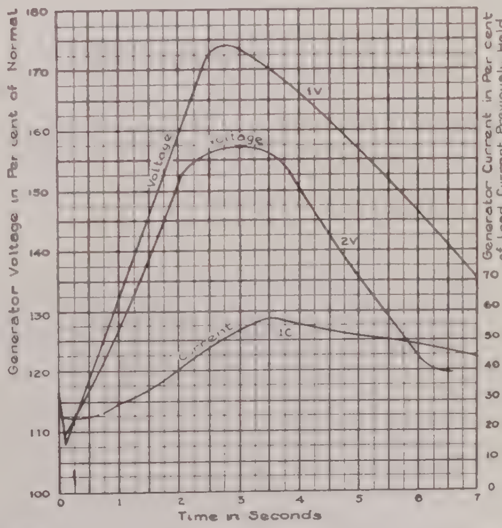


Fig. 4. ***Case 1.*** **6500-kw. Load Dropped by Tripping Transformer High-voltage Breaker. Direct-connected Exciter. No Regulator** ***(Test 4)***

Case 2. **6400-kw. Load Dropped by Tripping Transformer High-voltage Breaker. Direct-connected Exciter. Regulator in Operation** ***(Test 5)***

Load Dropped by Tripping High-voltage Transformer Breaker

Direct-connected Exciter Used

Fig. 4 shows the results of two tests, one taken with and one without the voltage regulator. In each case, load was dropped by opening the high-voltage transformer breaker. Here, as before, the voltage regulator was very effective in limiting the rise of voltage.

Allowing for the different amounts of load dropped, it is seen that when the load was tripped by the transformer high-voltage circuit breaker the voltage did not rise as high as when the load was tripped by the generator circuit breaker. This difference was due to the exciting current taken by the transformer after the high-voltage circuit breaker had been opened, which was load current for the generator. Curve *1C*, Fig. 4, shows how the transformer exciting current, or in other words, the generator load current, increased as the voltage became greater and greater after load had been dropped.

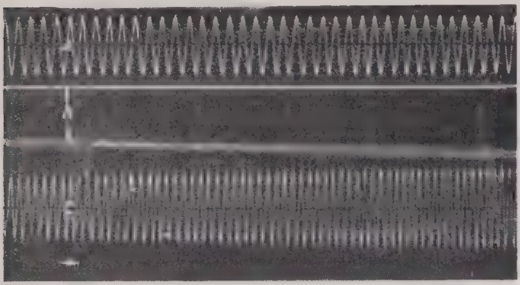
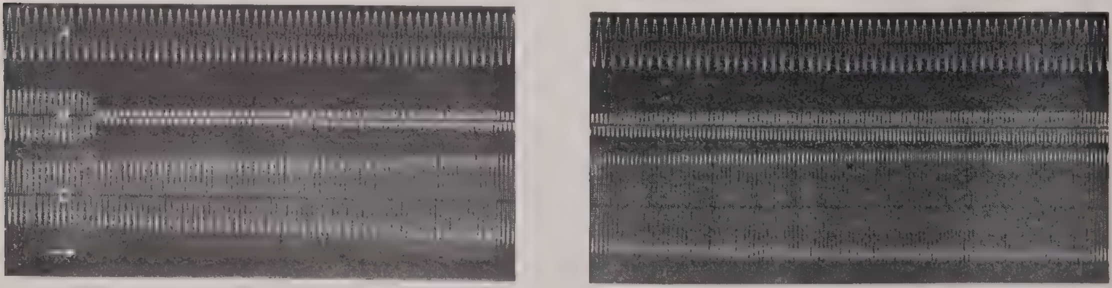


Fig. 5. 6400-kw. Load Dropped by Tripping Transformer High-voltage Breaker. Direct-connected Exciter. No Regulator. (*Test 6*)

A: 40-cycle timing wave
B: Exciter voltage
C: Generator voltage



Figs. 6a and 6b. 6500-kw. Load Dropped by Tripping Transformer High-voltage Breaker. Direct-connected Exciter. No Regulator. (*Test 4*)

A: 40-cycle timing wave
B: Generator current
C: Generator voltage

Figs. 6a and 6b show part of the oscillogram from which Curves *1V* and *1C*, Fig. 4, were taken. The oscillogram shows how the transformer exciting current and the generator voltage increased in value after load was dropped, the middle wave being the transformer exciting current and the lower wave the generator voltage.

Fig. 5 shows part of an oscillogram similar to that of Fig. 6a, with the exception that a slightly different load was dropped. The middle wave indicates exciter voltage instead of generator current. This middle wave gives a good indication of how the exciter voltage increased in value as the speed increased after the load was dropped.

Load Dropped by Tripping Substation Breaker

Direct-connected Exciter Used

Fig. 7 shows the results of two tests, one taken with and one taken without the voltage regulator, in which load was dropped by opening the substation circuit breaker. The voltage regulator was again very effective in limiting the voltage rise.

Curve *1V* of Fig. 7 shows a 118 per cent voltage rise, which is a greater rise than was obtained in any of the other tests. This is only natural when consideration is given to the fact that the charging current of the 40-mile line more than offsets the exciting current of the transformer, the effect of which was to boost the excitation of the generator.

Curve *2C*, Fig. 7, shows the generator current which is a resultant of transformer exciting current and line charging current. In this instance, the current curve has two peak values, the dip in the middle occurring at the time the voltage reached maximum.

Figs. 8a and 8b show parts of the oscillogram from which Curves *2V* and *2C* of Fig. 7 were taken. The middle wave of the oscillogram shows clearly the dip in the generator current mentioned, and also the many harmonics in the current wave. The lower wave of the oscillogram represents the generator voltage and shows the switching surge at the time the high-voltage transformer circuit breaker was tripped, and just how the voltage increased after the load was dropped.

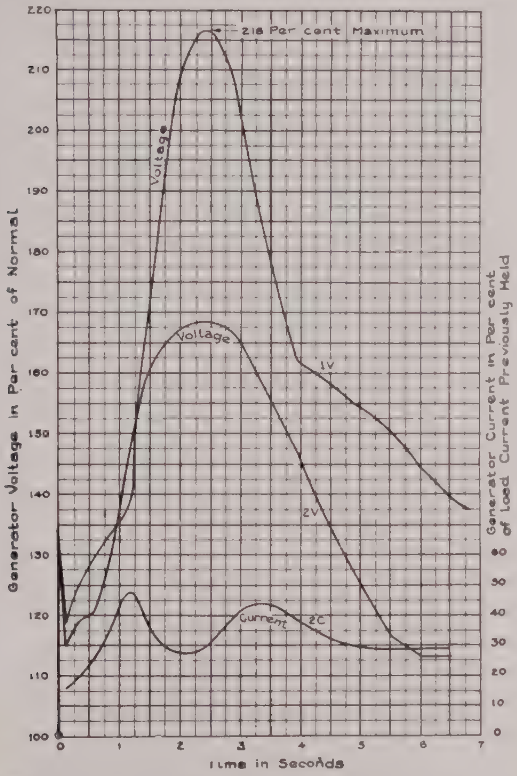


Fig. 7. *Case 1.* 6700-kw. Load Dropped by Tripping Substation Breaker. Direct-connected Exciter. No Regulator. (*Test 7*)
Case 2. 6100-kw. Load Dropped by Tripping Substation Breaker. Direct-connected Exciter. Regulator in Operation. (*Test 8*)

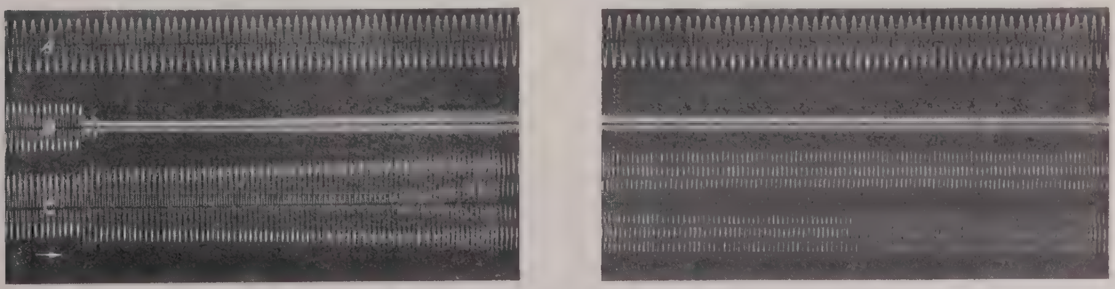
Voltage Reduction

The tests already described show the rapid and extensive rise of voltage that occurs when load is lost on a waterwheel-driven generator. Believing it desirable to check the voltage rise as soon as possible after load is dropped, a series of tests was made to determine the speed with which the generator open-circuit voltage could be reduced by three different methods. A tabulation covering these tests is given in Table III. Fig. 9 shows the results of three of these tests, each method being represented. Curve *a* shows the rate of voltage decrease when a block of resistance was placed in the exciter field circuit, this being accomplished by holding the voltage regulator contacts open. Curve *b* shows the rate of voltage decrease when the exciter field switch was opened, and Curve *c* the rate of voltage decrease when the generator field circuit breaker was tripped. Field discharge resistors were of course used in the latter two cases.

TABLE III

REDUCTION IN GENERATOR OPEN-CIRCUIT VOLTAGE

Test	Previous Voltage in Per Cent of Normal	Method of Reducing Voltage	Time in Seconds for Voltage to Decrease 50 Per Cent
16	143	Insert Resistance in Exciter Field Circuit	4.75
17	149	Open Exciter Field Switch	3.75
18	52	Trip Generator Field Breaker	0.90
19	100	Trip Generator Field Breaker	1.00



Figs. 8a and 8b. 6100-kw. Load Dropped by Tripping Substation Breaker. Direct-connected Exciter. Regulator in Operation. (*Test 8*)
A: 40-cycle timing wave *B:* Generator current
C: Generator voltage

Fig. 9 shows the advantage of tripping the generator field when it is desirable to reduce the generator voltage at a very fast rate.

Fig. 10 shows the oscillogram from which Curve *a* of Fig. 9 was taken. The middle wave of the oscillogram shows the way the exciter voltage decreased when a block of resistance was placed in the exciter field circuit.

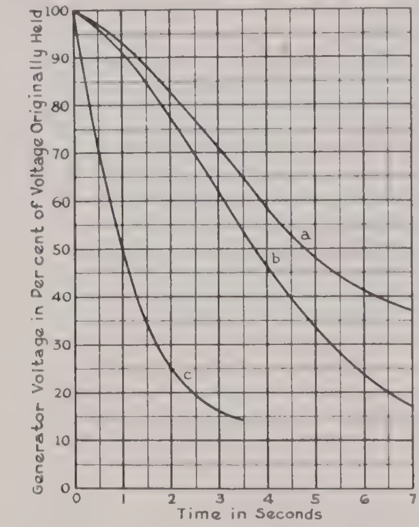


Fig. 9. Generator Open-circuit Voltage Decreased:
Case a: **by Inserting Resistance in Exciter Field Circuit.** (*Test 16*)
Case b: **by Opening Exciter Field Switch.** (*Test 17*)
Case c: **by Tripping Generator Field Circuit Breaker** (*Test 19*)

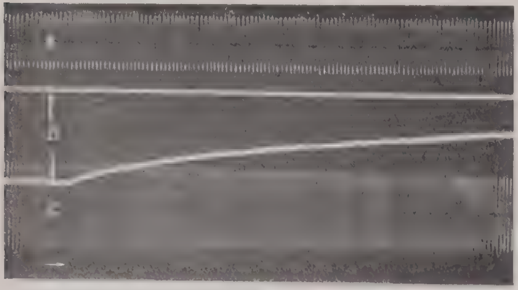


Fig. 10. Generator Open-circuit Voltage Decreased by Inserting Resistance in Exciter Field Circuit (*Test 16*)
A: 60-cycle timing wave
B: Exciter voltage
C: Generator voltage

Fig. 11 shows the oscillogram from which Curve *c* of Fig. 9 was taken, the generator field circuit breaker being tripped at a time when the generator was operating at normal voltage, no load. The middle wave of oscillogram shows how the generator field voltage decreased after the field circuit breaker was opened. It will be noted that the generator field excitation was reversed in polarity at the time the field circuit breaker was tripped.

Fig. 12 shows the effect of tripping the generator field circuit breaker, as well as the generator main circuit breaker, after the load had been dropped by opening the high-voltage transformer circuit breaker by hand. Curves *1S* and *2S* show the rise in speed and Curves *1V* and *2V* show the corresponding voltage changes, when load was dropped. The difference in the two speed curves is due to the fact that more load was dropped in Case 1 than in Case 2.

The voltage Curves *1V* and *2V* are also different. In Case 1, the generator and field circuit breakers were tripped by an over-voltage relay set at 115.5 per cent of normal voltage. In Case 2, the generator and field circuit breakers were tripped by an over-frequency relay set at 63 cycles or 105 per cent of normal frequency. In each case, auxiliary contactors were used with the relays so arranged that the trip circuits of the generators and field circuit breakers would be energized at the same time.

Over-voltage and Over-frequency Relays

The curves in Fig. 12 give information regarding the operation of the relays as well as information regarding the voltage and speed changes. In Case 1, the generator and field circuit breakers were tripped sooner than in Case 2. This was due to the fact that the over-voltage relay in Case 1 was operated by the initial voltage impulse which reached approximately 130 per cent of normal, while

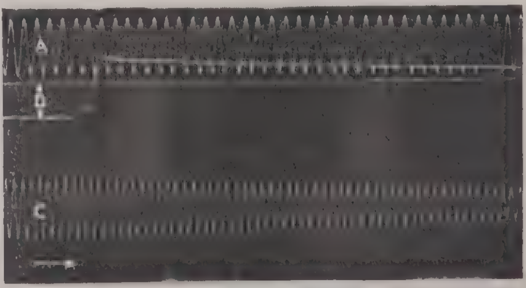


Fig. 11. Generator Open-circuit Voltage Decreased by Tripping Generator Field Circuit Breaker. (*Test 19*)
A: 40-cycle timing wave
B: Generator field voltage
C: Generator voltage

the over-frequency relay in Case 2 did not operate until approximately a quarter of a second later when the speed reached 105 per cent of normal.

Fig. 13 shows part of the oscillogram from which Curves *2S* and *2V* of Fig. 12 were taken. The middle wave on the oscillogram represents the generator current and indicates clearly the time when the high-voltage transformer circuit breaker opened and also the time when the generator circuit breaker opened. By use of the 40-cycle timing wave, it is found that the generator circuit breaker opened approximately 0.73 second after the high-voltage transformer circuit breaker was tripped.

Three different tests are represented in Fig. 14. An over-voltage relay was used in Case 1 and Case 2, but in Case 3 a combination relay of both over-voltage and over-frequency was used. In the latter case, the over-voltage element was set at 115 per cent normal voltage and the over-frequency element was set at 105 per cent normal frequency. The contacts of both elements were placed in series, so the tripping circuit of the generator breaker would not be energized until each set of contacts had been closed. An analysis of the curves shows that the contacts of the over-voltage relay closed approximately 0.5 second later than the closing of the over-frequency relay contacts.

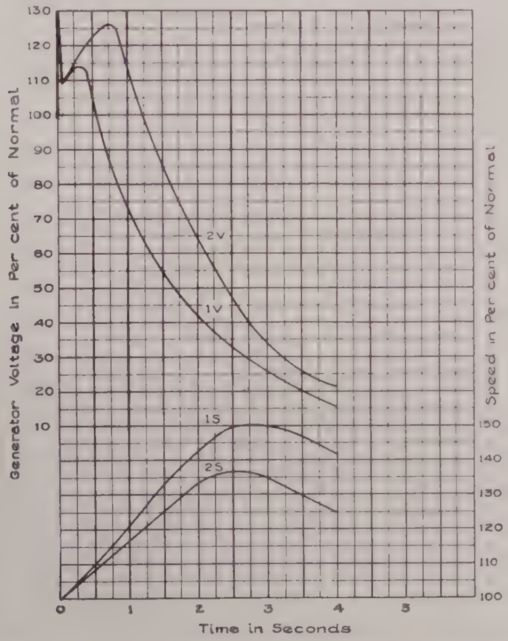


Fig. 12. *Case 1.* 6500-kw. Load Dropped by Tripping Transformer High-voltage Breaker. Direct-connected Exciter. Regulator in Operation. Over-voltage Relay Tripped Generator Breaker. (*Test 9*)
Case 2. 6150-kw. Load Dropped by Tripping Transformer High-voltage Breaker. Direct-connected Exciter. Regulator in Operation. Over-frequency Relay Tripped Generator Breaker. (*Test 10*)

In Case 1, the relay tripped the high-voltage transformer circuit breaker, while in Case 2 the relay tripped the generator circuit breaker. In Case 1, the transformer exciting current furnished load for the generator; therefore, the voltage did not rise as high as it did in Case 2, where the generator had no load after the generator breaker was tripped.

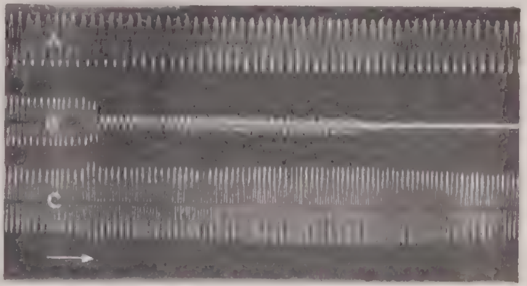


Fig. 13. 6150-kw. Load Dropped by Tripping Transformer High-voltage Breaker. Direct-connected Exciter. Regulator in Operation. Over-frequency Relay Tripped Generator Breaker (*Test 10*)
A: 40-cycle timing wave
B: Generator current
C: Generator voltage

Fig. 15 shows part of the oscillogram from which Curve *2V* of Fig. 14 is taken. The middle wave of the oscillogram represents the voltage on the high-voltage side of the transformer. The small voltage indicated after the generator breaker was opened was induced from a 110,000-volt, 60-cycle line, which paralleled the line being used for these tests.

Generator Circuit Breaker and Relay Tests

In order to check the operation of the relays, two tests were made with the use of the oscillograph, one to determine the operating time of the generator circuit breaker and the other to determine the operating time of the over-voltage relay. The results of the tests are shown in Table IV.

TABLE IV

OPERATING TIME—GENERATOR CIRCUIT BREAKER AND OVER-VOLTAGE RELAY

Test	Equipment	Operating Time Seconds
20	Generator Breaker and Relay	0.21
21	Generator Breaker	0.11

General Considerations and Calculations

Voltage Regulation

Due to regulation, the voltage of an alternating-current generator carrying full load at normal speed and voltage will generally rise from 25 to 35 per cent above normal when load is lost, providing the speed and excitation remain constant.

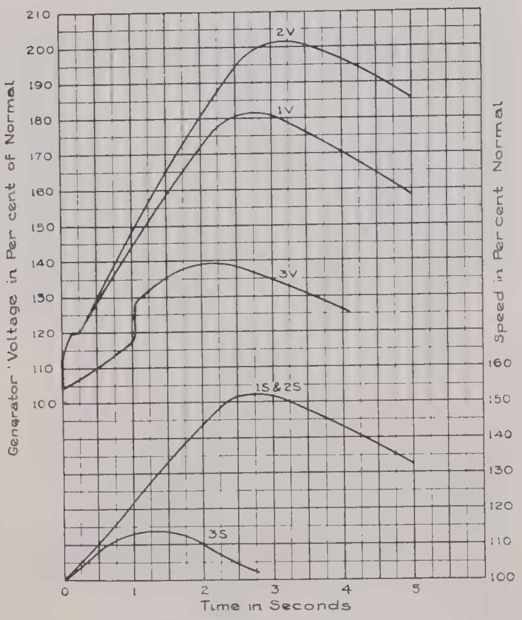


Fig. 14. *Case 1.* 6700-kw. Load Dropped by Tripping Substation Breaker. Direct-connected Exciter. No Regulator. Over-voltage Relay Tripped Transformer High-voltage Breaker. (*Test 11*)
Case 2. 6700-kw. Load Dropped by Tripping Substation Breaker. Direct-connected Exciter. No Regulator. Over-voltage Relay Tripped Generator Breaker. (*Test 12*)
Case 3. 3500-kw. Load Dropped by Tripping Transformer High-voltage Breaker. Direct-connected Exciter. No Regulator. Combination Over-voltage and Over-frequency Relay Tripped Generator Breaker. (*Test 13*)

Part of this rise in voltage is instantaneous and part takes place over an interval of time. Consider the 8500-kv-a., 6600-volt, alternating-current generator used in the tests just described, and assume that it is carrying a load of 5900 kw., 0.83 per cent power-factor, as in test No. 1.

When carrying this load, the calculated internal or generated voltage is equal to 111 per cent of the terminal voltage. The internal voltage differs from the terminal voltage by the amount of impedance drop in the stator winding. If the load just mentioned is dropped, the terminal voltage will instantly rise to a value equal to the internal voltage because the flux to produce this voltage is already present in the stator and because the impedance drop in the stator winding disappears as soon as load is dropped. Referring to Fig. 2, this instantaneous voltage rise is shown by line *c d*, the calculated value being 111 per cent and the test value being 112 per cent of normal voltage.

Using calculations and assuming that the speed and excitation remain constant, the voltage will increase from 111 per cent voltage to the open-circuit voltage. This rise of voltage is shown by Curve *6*, Fig. 2, and takes place over an interval of time, because after the load is tripped and the armature reaction disappears, time is consumed in building the stator flux up to a value corresponding to the field m.m.f.

For an average generator on which full load is lost, this time may be assumed to be two seconds, but varies to some extent according to the size and design of the machine in question.

Prime Mover

As the governors of waterwheels and steam turbines are speed devices, a change in load is always accompanied by a change in speed. Given sufficient time, the new output of energy will be produced at a new steady speed. (Only by readjustment of the governor can the new output be produced at the previous speed.) When the decrease of load is great and sudden, the speed will rise higher than the ultimate speed, this over-shooting being due to the inability of the governor system to follow the speed of the turbine rotor quickly enough.

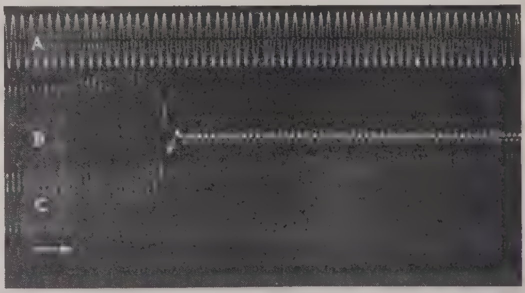


Fig. 15. 6700-kw. Load Dropped by Tripping Substation Breaker. Direct-connected Exciter. No Regulator. Over-voltage Relay Tripped Generator Breaker (*Test 12*)

A: 40-cycle timing wave
B: High-tension voltage at transformer terminals
C: Generator voltage

The overspeed of water turbines when full load is lost varies according to the horse power of the turbine, the time taken to close the guide vanes, the WR^2 of the combined generator and turbine unit, the revolutions per minute, and the length of the penstocks. However, these different factors combine in such a way that, for an ordinary design of water turbine, the overspeed is usually from 25 to 35 per cent when the load is dropped.

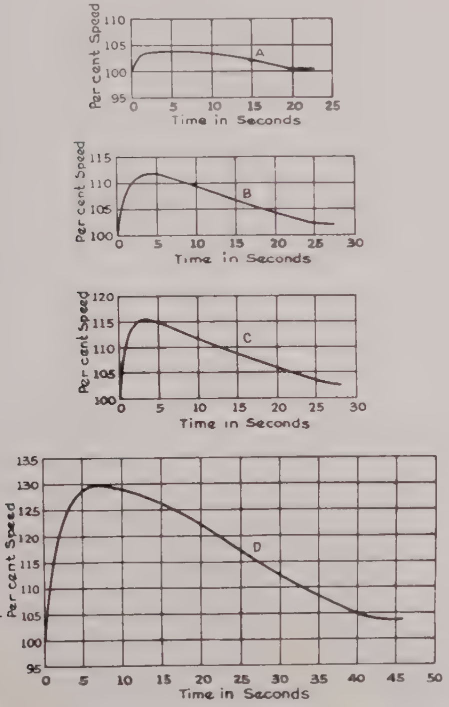


Fig. 16. Load Rejection on a 44,000-kw. Water Turbine

A: 39.8 per cent load dropped
B: 58.0 per cent load dropped
C: 67.0 per cent load dropped
D: 100.0 per cent load dropped

Fig. 16 shows some typical speed-time curves indicating the rise in speed on a large water turbine when different amounts of load were dropped. In this particular case, the speed rose to 130 per cent of normal, when full load was dropped.

In the tests referred to in the first part of this article, the speed regulation was greater than customary for the reason already given, namely, the waterwheel governor had not received final adjustment.

The maximum speed attained by a steam turbine when load is suddenly removed is much less than that attained by a water turbine under similar conditions.

Tests taken on a 30,000-kw. steam turbine show that when full load was dropped the governor action was such that the maximum speed attained was only four per cent above normal. This maximum speed was reached in one second. Upon dropping a 75 per cent load on the same turbine a maximum speed rise of 2.75 per cent normal was attained in 0.9 second. Even if the emergency governor of a steam turbine is called upon to operate, the speed will generally not rise above 110 per cent of normal.

In view of the foregoing, the danger from the over-voltage on steam stations is not as great as on hydroelectric stations.

Generator Excitation

Field excitation for alternating-current generators is usually obtained from one of the following sources:

(1) Direct-current bus.
(2) Direct-connected exciter.
(3) Exciter motor-generator set.

The maximum over-voltage obtained when load is dropped depends, to some extent, on which method of excitation is used, as a direct-connected exciter will overspeed with the generator when load is dropped. The same is true of an exciter motor-generator set if the motor of the set receives power from a circuit connected to the alternating-current generator which loses its load.

An increase in the speed of the exciter causes an increase in the exciter voltage, which, in turn, causes an increase in the alternating-current generator field current and therefore a further rise in the alternating-current generator voltage.

For exciters generally used, the armature voltage increases approximately as the square of the speed, as the speed is increased above normal. The alternating-current generator field current increases in direct proportion to the increase in exciter voltage providing the resistance in the field circuit remains the same, but the alternating-current generator voltage will not increase in direct proportion to the increase in its field current due to saturation of the iron in the generator magnetic circuit. However, if a waterwheel-driven generator having a direct-connected exciter drops load, the field current will rise to such an extent that the open-circuit voltage will usually reach the upper part of the saturation curve, which is nearly flat.

Referring again to Fig. 2, the voltage rise shown by Curve *6* assumes no increase in speed when load is dropped, and assumes the generator to be separately excited. If the speed is increased and field excitation held constant, the voltage will actually rise above this Curve *6* in direct proportion to the increase in speed. This is true because the open-circuit voltage of an alternating-current generator is always proportional to the generator speed, providing the excitation remains constant.

Now assume that the 8500-kv-a. generator has a direct-connected exciter and that it is connected to a waterwheel having a speed characteristic as shown by Curve *1S*, Fig. 2. Curve *3*, Fig. 2, shows how the generator voltage increases to 132.5 per cent of normal assuming an over-speed on the exciter, but no over-speed on the generator. (This is a physical impossibility, but is suggested as a step toward determining the actual voltage.) The instantaneous increase in voltage *cd* is the same as before. For the voltage rise indicated by Curve *3*, a time lag of three seconds has been assumed, which takes into consideration the lag of flux change in both the exciter and the alternating-current generator.

When the load is dropped, the generator, as well as the exciter, overspeeds; therefore, the calculation of the actual generator voltage curve for this condition involves increasing the value of the voltage points on Curve *3*, in accordance with the increase in speed, as shown on speed Curve *1S*. The resulting calculated values of actual generator voltage are indicated by the circle points falling on or near Curve *1V*.

Voltage Regulators

In case a generator voltage regulator is used in connection with a generator that loses load, the regulator will of course try to keep the voltage from rising. As soon as load is lost, the regulator contacts at once open and a block of resistance is inserted in the exciter field circuit. If a large amount of load is dropped on a waterwheel-driven generator, the generator voltage rises in spite of the fact that a block of resistance has been placed in the exciter field circuit, principally because the flux change in the exciter and the generator is relatively slower than the speed change.

Curve *a* of Fig. 9 represents a voltage regulator test, as already mentioned. This curve is reproduced in Curve *4* of Fig. 2 for use in making calculations. For convenience, the starting point of the curve is raised to 111 per cent generator voltage and all other points are raised in the same proportion.

It was previously stated that Curve *3* of Fig. 2 shows how the generator voltage increases, assuming an over-speed on the exciter, but no over-speed on the generator. By combining Curve *3* and Curve *4*, a resultant curve is obtained, as shown by Curve *5*, which represents approximately the change in voltage when a load of 6100 kw., 0.83 power-factor, is dropped, a direct-connected exciter and a voltage regulator being used.

Curve *3* is used to take care of a 6100-kw. drop of load, as well as a 5900-kw. drop of load, because, if two curves were plotted, one would fall practically on the other. Now, increasing the voltage points on Curve *5* in accordance with the increase of speed, as shown by Curve *2S*, final calculated results are obtained as shown on the small triangles. These calculated points fall reasonably close to the test Curve *2 V*.

Amount and Power-factor of Load Dropped

The per cent voltage regulation of a generator and the per cent speed regulation of a turbine being greater for full load than for part load, it is obvious that the loss of full load on a generator will cause a greater rise in voltage than dropping part load.

As the power-factor of a load being furnished by a generator is decreased below unity (assuming constant kilowatt output), the field excitation, the kilovolt-ampere output, and the internal generated voltage increase. Therefore, the lower the power-factor of the load dropped, the greater will be the rise in voltage.

Conclusions

It is not considered good practice to subject a transmission system to high over-voltages, especially if they are of long duration, because such over-voltage might cause damage to the generators, motors, transformers, lightning arresters, lines, insulators, and other equipment connected to the system.

Each piece of apparatus is designed for a particular maximum voltage, should be tested in accordance with A. I. E. E. Standardization Rules, and should operate continuously and successfully at that voltage under normal operating conditions. If the voltage is increased above normal, apparatus or equipment may or may not fail, according to the following factors:

(1) Maximum over-voltage obtained.

(2) Duration of over-voltage, taking into consideration the speed with which the voltage is increased or decreased.

(3) Factor of safety in insulation and design of apparatus or equipment.

In other words, the time element of over-voltage must be taken into consideration as well as the maximum over-voltage. For example, a piece of apparatus may withstand an impulse voltage of double normal or more, when the duration of the impulse is a fraction of a cycle, but may fail if subjected to a voltage of much less value when applied continuously for several seconds at normal frequency.

In general, it is desirable to design any piece of apparatus so that it has as high a factor of safety against failure as is consistent with an economical design. The proper balance between factor of safety and economy of design depends largely on the principle underlying the design. In some kinds of apparatus, such as transformers, a high factor of safety is possible; in others, as lightning arresters, the same high degree of safety with over-voltage is incompatible with the proper functioning of the device.

An attempt should never be made to capitalize the factor of safety by operating a piece of apparatus at voltages above normal. Furthermore, it should not be assumed that the factor of safety will take care of any over-voltage that may exist momentarily on a system.

Although the apparatus treated thus may not fail immediately, the insulation or other parts may be weakened, so that by repeating or continuing the conditions of over-voltage, eventual failure is invited.

Total loss of load, and therefore dangerous over-voltage, may occur on any hydroelectric station having only one or two outgoing lines. If all, or nearly all of the power, is fed out from the station over one line, then in case of trouble it is quite possible that load on this line will be lost, particularly if the line is adequately protected by relays. If a station has two outgoing lines, both line breakers may occasionally trip automatically; also, if two outgoing lines are used, one line may be under repair, in which case, all of the power would be transmitted over the second line. The situation would then be the same as though only one line existed.

When the load is fed out over three or more lines, there is much less likelihood of complete loss of load; therefore, the same precautions are not as essential as in the case of stations having only one or two circuits.

The contacts of the over-speed and the over-voltage relays may be connected either in multiple or in series. If they are connected in multiple, the over-voltage relay should be given a sufficiently high setting to prevent it operating in case of ordinary switching surges. If the contacts are connected in series, the over-voltage, as well as the over-speed relay, may be given a rather low setting.

Spier Falls Plant in Which Mr. Burnham's Voltage Rise Tests Were Conducted

Ferrocarrils de Cataluna y Sarria—A Spanish Electrification

By H. C. Hutchinson
Railway Engineering Department, General Electric Company

Though the customs and the working conditions of peoples in various countries may differ somewhat with climate and environment, the differences are never so great but that electricity is of service everywhere, and by the same fundamental means. Thus we find in the interurban electrification surrounding Barcelona, Spain, the same types of motors, the same substations, overhead line construction and rolling stock as are in use in the United States and other countries. This railroad has followed the growing practice in many large communities, in electrifying its city and interurban track, in order to realize the added flexibility, the lower operating cost, and the superior service of electric transportation.—Editor.

Among the factors which have combined to make Barcelona the largest city in Spain and the center of Spanish industry and commerce are its excellent transportation systems, prominent among which is that of the Ferrocarrils de Cataluna Y Sarria. This railroad was designed and built and is now being operated according to the best American practice. This property for a number of years has been under the control and management of the Canadian General Finance Co. of London.

Most of the neighboring country consists of mountain ranges often densely wooded, rich in minerals and frequently intercepted by deep ravines. In 1924, the population of the city and its environs approximated 1,800,000 people. It was through such a territory that a wide guage steam railroad was built in 1856 connecting the center of Barcelona with Sarria, a total distance of 4.7 km. (3.9 mi.). In 1906 steam service was discontinued and electric operation started using a trolley pressure of 600 volts. In 1916 the line was extended to Tarrasa, thereby making a total route length of 29.2 km. (18.1 mi.). On this extension the present scheme of 1200-volt operation beyond the municipal or corporate limits of Barcelona was instituted. In 1920, 1200-volt operation was again extended from San Cugat, the end of the double track section from Barcelona, by the construction of a branch line to Sabadell, a distance of 10.8 km. (6.7 mi.). It is interesting to recall that when 1200-volt operation was started, the economies of high-voltage direct current for heavy traffic conditions had been thoroughly demonstrated.

The construction of this road compares favorably with the best American practice. Its terminus in Barcelona lies in the very heart of the business district. The company owns its right of way through the city of Barcelona, where it crosses the streets at grade. It now has under consideration the elimination of the grade crossings by placing the tracks underground, thus not only making possible the use of the valuable strip of land embraced in the right of way for boulevard purposes, but also to permit of connecting with the recently completed municipal subway system.

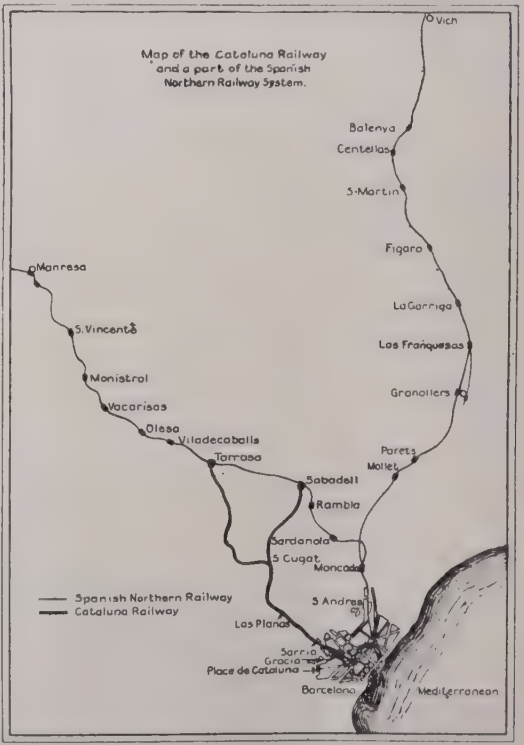


Fig. 1. Map of the Cataluna Tramway System and Interconnecting Lines of the Spanish Northern Railway

The extension from San Cugat to Sabadell, recently opened to traffic, is built on most substantial lines as regards track, roadway and culverts. Double tracking has been anticipated throughout. The level of the station platforms on this line, as well as on the remainder of the system, is 40 cm. (15.5 in.) above the top of the rail to obviate the passenger loading and unloading problem.

The distance from Barcelona to the principal stations together with their respective elevations are shown in Table I.

Trains are operated at 600 volts from Barcelona to Pie de Funicular, a distance of 6.7 km. (4.6 mi.), where they change over to the 1200 volts used throughout the remainder of the system. Municipal regulations prohibit the use of 1200-volt operation within the city. The outlying termini of Tarrasa and Sabadell are also on the main line of the Spanish Northern Railway as shown by the map, (Fig. 2).

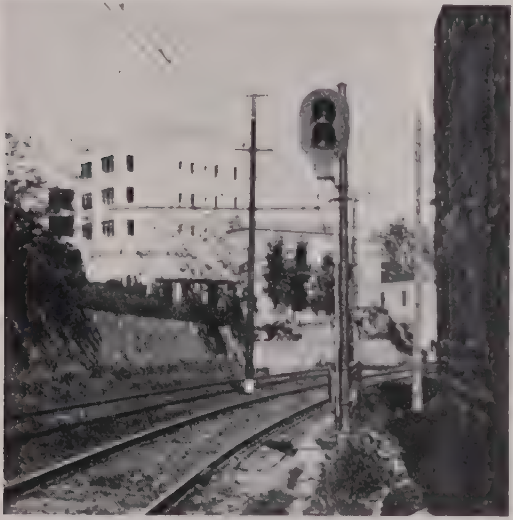


Fig. 2. Typical Double Track Section on the Cataluna Tramway System, Showing Overhead Construction and Signal System

Rolling Stock

The rolling stock consists of 18 motor cars, each equipped with four 100-h.p. motors and type M control; twelve motor cars equipped with four 55-h.p. motors each and PC automatic control; three work cars each equipped with four 80-h.p. motors and type M control. In addition 12 motor cars are equipped by other manufacturers and nine trail cars were built by the railway company. All the passenger cars are equipped with a pneumatic door opening and closing device, which also lowers the steps for the end entrance cars and projects the steps horizontally for the center entrance cars.

The eighteen cars which are equipped with 100-h.p. motors have a total weight without passengers of 44 metric tons (48.4 tons). Trains of two motor cars are usually operated with a trailer in the center weighing 28 metric tons (approximately 31 tons), thus making the total train weight 108 metric tons (119 tons). The motor cars have 36-in. wheels with axles on each truck spaced 6 ft. 6 in. apart. The cars of this type are arranged for end entrance. Both motor and trail cars seat 60 passengers, except in the case of some of the second class cars where the space reserved for express or baggage compartments reduces the seating capacity to 54. All of these cars are used in the express or limited service between Barcelona and Tarrasa, or Sabadell.

TABLE I

Station	DISTANCE		ELEVATION	
	Km.	Mi.	M.	Ft.
Barcelona...	0	0	17.8	58.3
Gracia......	2.12	1.31	58.1	190
Sarria......	4.74	2.94	100.8	330
Pie de Funicular.	6.74	4.17	186.8	612
Las Planas..	9.3	5.8	219.0	718
San Cugat...	14.58	9.05	131.8	432
Rubi.......	20.41	12.7	121.0	396
Tarrasa.....	29.41	18.1	265.1	818
San Cugat...	14.58	9.05	131.8	432
Sabadell....	25.03	15.5	187.2	558

The twelve cars equipped with 55-h.p. motors are of the center entrance type with 33-in. wheels and weigh 32.2 metric tons (35.4 tons) without load. They are equipped with PC–101 automatic control designed to operate at either 600 or 1200 volts. A commutating switch is used to make the necessary changes in motor and control connections for operation on 1200 volts. Each car seats 54 passengers and trains are made up of one, two or three motor cars with no trailers. These cars are primarily designed for use on the 600-volt section between Barcelona and Sarria, but they are also available for extra service to Las Planas or any part of the line on Sundays and Feast days to supplement the heavy through equipment.

The 12 cars equipped by other manufacturers seat 56 people, weigh 36 metric tons (39.6 tons) and have 33-in. wheels. Six cars have trucks with 6-ft. 6-in. wheel base, while the remainder have a 7-ft. 6-in. wheel base, using trucks manufactured by the Railway Company. They are also equipped with General Electric air brakes.

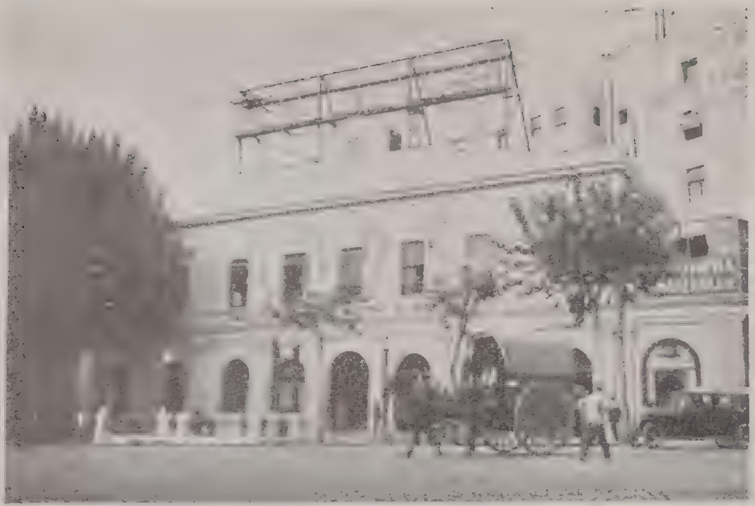


Fig. 3. Terminal Building in Barcelona

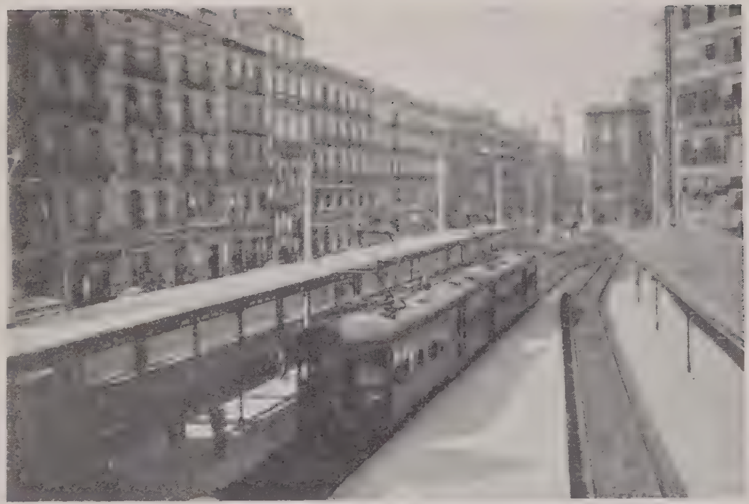


Fig. 4. Two-car Train at the Barcelona Station

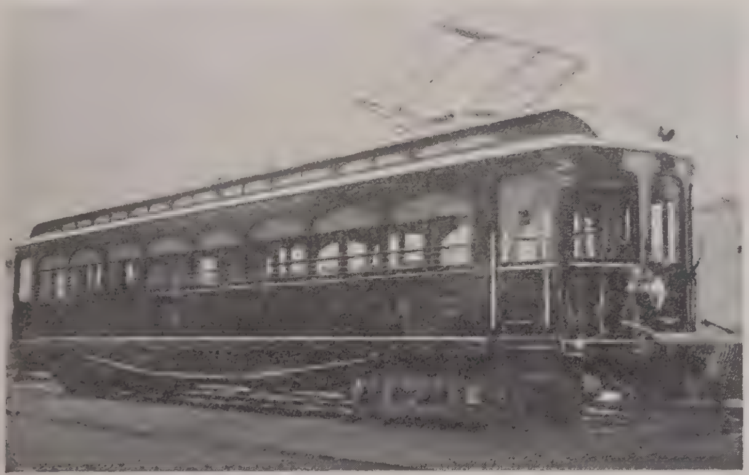


Fig. 5. Typical Third-class Car for Interurban Service

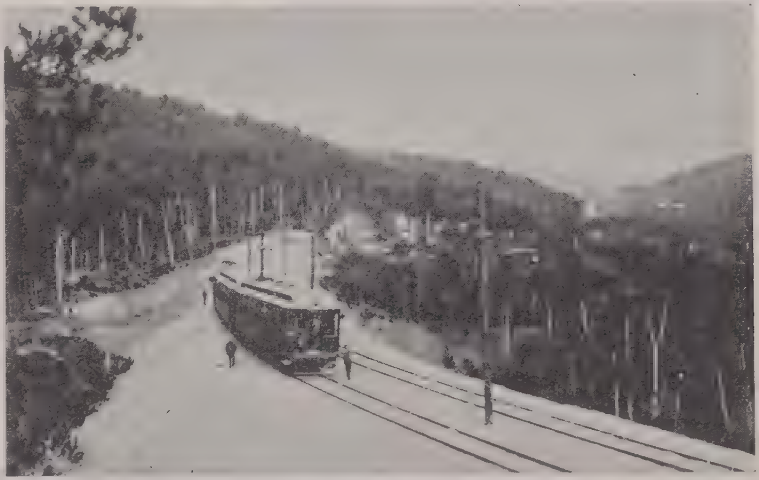


Fig. 6. Double-track Right-of-way in a Mountainous Section

All of the motor cars are equipped with a single slider pantograph for collecting the current. A bus line is provided so that the failure of an individual pantograph will not interrupt the service. Pressures of about 35 lb. are used and the pans are kept well greased, which accounts for the negligible wear on the trolley wire and the sparkless collection of current.

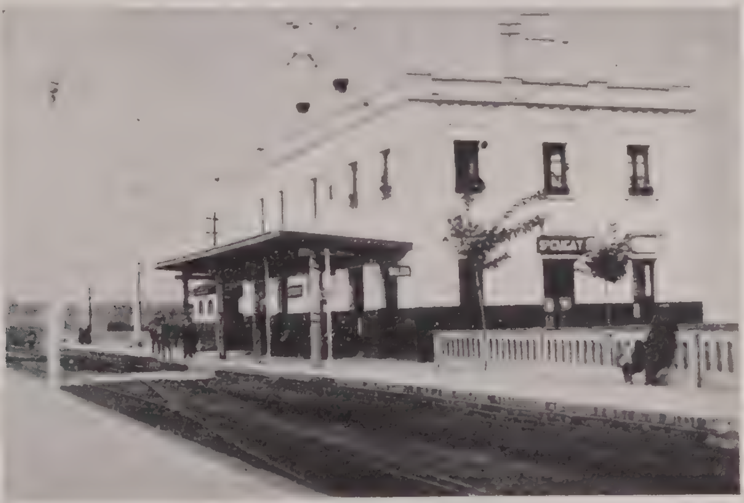


Fig. 7. San Cugat Station, Where the Double-track Section Terminates

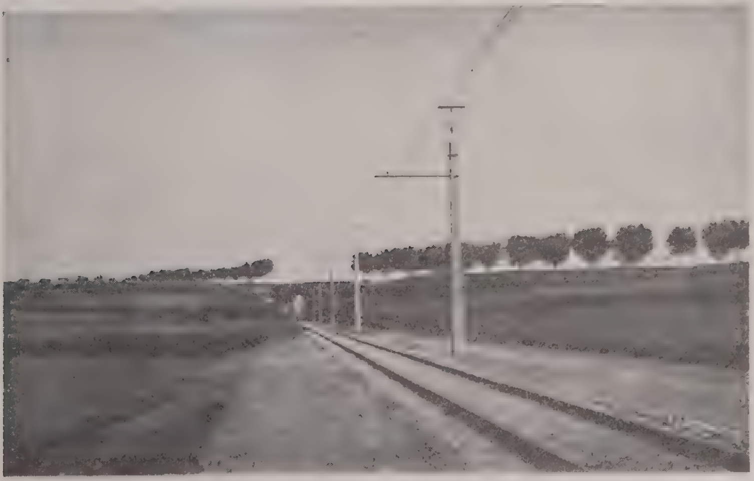


Fig. 8. Tangent Track Construction, with Concrete Trolley Poles

Overhead System

Simple catenary construction with 7-point suspension is used for the overhead system. A stranded steel messenger of 1.5 cm. (0.6 in.) diameter is used to support the 4/0 grooved bronze alloy trolley wire. The railway company has experimented with hard drawn copper messenger and as a result this material will probably be used for future extensions.

Much of the line material such as pull-offs, overhead switches and splice sleeves, is manufactured by the railroad company at its Sarria shops. On the older work no automatic device is used for adjusting the tension in the trolley and the messenger, but on the newer work between San Cugat and Sabadell, arrangements have been made to use an automatic tensioning device consisting of compression springs inserted in the trolley wire anchorages, 750 m. (2460 ft.) apart.

The trolley messenger in the 600-volt zone is supported by corrugated tubular insulators placed on the pole brackets, The usual pin type messenger insulator is, however, used for the higher voltage.

For the original installation general use was made of wood strain insulators. A preference now exists for the porcelain fluted strain insulator, therefore this type will probably be substituted on future extension work.

The distance from the top of the rail to the trolley wire may be taken at an average of 6 m. (19.7 ft.). When approaching tunnels the wire is dropped with a slope of about 0.5 per cent to the lower elevation limited by the clearances.

On the older work between Barcelona and Tarrasa tubular steel and wood poles are used, but on all replacements, as well as on the newer work between San Cugat and Sabadell, concrete poles are favored, due to their lower cost and practically infinite life. A piece of two-inch pipe is cast into the top of these poles for supporting the bracket carrying telephone and other small wires. The pole brackets for supporting the catenary system are made of two angles bolted to a steel casting, which is clamped to the pole with bolts. These castings are symmetrical, thus making provision for carrying brackets on both sides of the pole, which arrangement will be necessary if a second track is added. All poles have a basic spacing of 45 m. (147.5 ft.) on tangent track with suitable reductions on curves. The face of each pole is 1.2 m. (3 ft. 11 in.) from the center of the nearer track rail.

Shops

The repair shops for the system are located at Sarria. An extension has recently been built principally to take care of new construction work which is carried on in addition to the regular maintenance work. This work includes the manufacturing of steel cars, most of the line material needed, and such specialties as roller bearing trucks. The maintenance work on the line is facilitated by the use of three work car locomotives which are equipped with 3-ton air operated cranes.

Tracks

The tracks are laid with a 100-lb. steel rail, which is American made. This has recently been substituted for 85-lb. rail, which in turn replaced 60-lb. rail in 1916. Continuous rail joints are used. Screw spikes fasten the rail to oak ties which are treated and have a life of about 14 years. Crushed stone is used for ballast.

Power and Substations

Substations equipped with apparatus furnished by the General Electric Company are located at Barcelona, Sarria and San Cugat. The equipment comprises six 3-unit, 4-bearing motor-generator sets, each consisting of a synchronous motor rated at 1900 kv-a., 0.6 p.f., 750 r.p.m., 6000 volts, direct-connected to two 500-kw., 600/650-volt generators, one on each end of the shaft. An exciter rated 16 kw., 125 volts, is mounted on one end of the shaft of each unit. These motor-generator sets are so arranged that the two 500-kw. generators may be operated in parallel for 600-volt supply or in series for 1200-volt supply.

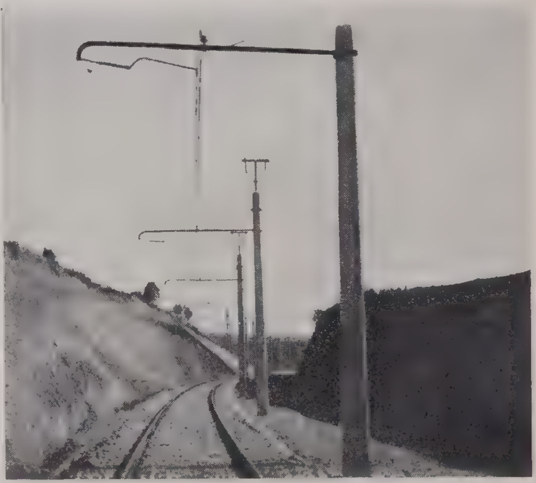


Fig. 9. Method of Supporting Feeder Wire on Curved Sections

Three-phase, 50-cycle power is supplied from the lines of the Ebro Irrigation and Power Co. at a pressure of 25,000 volts. This is stepped down through transformers in each substation to the 6000 volts used for the synchronous motor.

The Barcelona substation, which contains one set, is always operated at 600 volts. The San Cugat substation, which contains two sets, is always operated at 1200 volts, while the Sarria substation, which contains three sets, is normally operated at 600 volts. In an emergency, however, such as the failure of energy supply from the San Cugat station, any one of the three motor-generator sets at Sarria may be operated at 1200 volts.

The power is distributed to the system as shown in Table II.

This feeder arrangement, supplemented by the usual taps to the trolley wire at intervals of 100 m. (328 ft.), provides excellent voltage conditions at all points on the line.

Service and Statistics

Between Barcelona and Sarria a local service using one, two, or three motor cars for each train, with a normal five-minute headway, which is reduced to three minutes during the rush periods, prevails throughout the day. The headway is increased in the late evening to 15 minutes until the last trip at 2:30 a.m. For the through express service, trains leave Barcelona on the hour for Tarrasa and at quarter of the hour for Sabadell. These trains in general consist of three cars, i.e., two motor cars with a trail car in the center.

The following system statistics are available for 1923:

Car kilometers (motor car)	3,019,000	(1,870,000 mi.)
Car kilometers (trail car)	792,000	(452,000 mi.)
Freight-car kilometers....	3,908	(2,430 mi.)
Passengers carried (2nd class).......		2,464,291
Passengers carried (3rd class).......		15,038,223
Average rate of fare per passenger (2nd class)....................		48.2 centimos
Average rate of fare per passenger (3rd class)....................		34.32 centimos

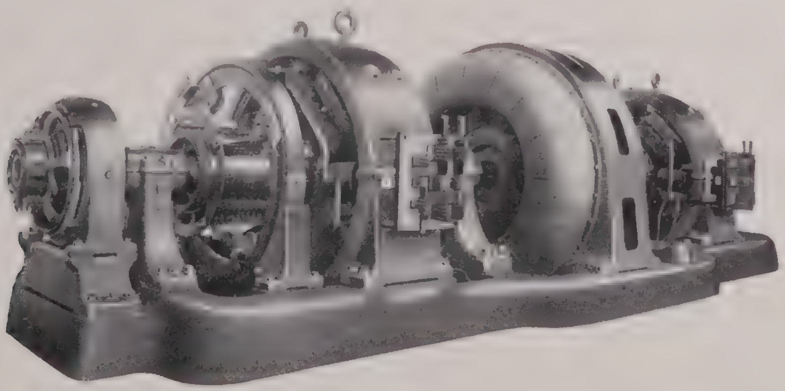


Fig. 10. Three-unit Synchronous Motor-generator Set which May be Operated as Two 650-volt Units or Tied Together for 1300-volt Service

TABLE II

Substation	Location of Feeders	Feeder Cap. in Cir. Mils.
Barcelona....	Barcelona to Sarria	500,000
Sarria.......	Sarria to Gracia......	1,000,000
	Sarria to Gracia......	500,000
	Sarria to Bueno Nova.	500,000
	Sarria to Bueno Nova.	500,000
	Sarria to Tunnel No. 2	500,000
	Sarria to Pie de Funicular.............	500,000
	Sarria to Las Planas..	500,000
San Cugat...	San Cugat for 3 km. (1.85 mi.) toward Barcelona.........	500,000
	San Cugat for 3 km. (1.85 mi.) toward Barcelona.........	500,000
	San Cugat to Las Planas	5/0 messenger
	San Cugat to Sabadell	250,000
	San Cugat to Tarrasa.	250,000
	San Cugat to Rubi....	250,000
	San Cugat to Rubi....	5/0 messenger

The running time for normal operation is as follows:

Barcelona–Sarria—Local 10 minutes.
Barcelona–Sarria—Express 8 minutes.
Barcelona–Tarrasa—Express 49 minutes.
Barcelona–Sabadell—Express 39 minutes.

The terminal at Barcelona is especially designed to handle the large crowds which use the line. Platforms are so arranged that when a train arrives the incoming passengers are discharged on one side, while the out-bound passengers are entering on the opposite side, thus avoiding congestion.

Information and illustrations for the preparation of this article have been obtained with the assistance and co-operation of Mr. Robert Grinnell, Director of the Railroad Co. and Mr. A. I. Totten of the General Electric Co.

Studies in the Projection of Light

PART XVII

DESIGN DATA OF ELLIPSOIDS AND HYPERBOLOIDS

By Frank Benford

Physicist, Illuminating Engineering Laboratory, General Electric Company

A customary use of the ellipsoid is to secure a concentration of light at a focus while the hyperboloid is employed to secure a greater beam width than is possible with a paraboloid. The distinction between the two thus seems clear enough from both mathematical and optical considerations, and therefore it may come as a surprise to many to find that under certain conditions the form taken by the beam beyond the conjugate focus of the ellipsoid is identical in every particular with a beam from a hyperboloid. There is thus a choice of forms that may be of great convenience to the reflector designer who must of course consider many things not strictly of an optical nature. The conditions under which optically equivalent reflectors may coincide in diameter, depth, focal length, or other features are investigated; and at the end of this installment the author has tabulated a series of equations so that an ellipsoid or hyperboloid may readily be computed from three given properties, such as the light collecting angle, the width of beam, the eccentricity, or the length of the axes.—Editor.

Optical Equivalence

For short-range projection, say for a matter of several feet, the ellipsoid is used as a concentrating device, but after the light has passed the image point it becomes identical with the beam from a hyperboloid. This fact will be demonstrated later. The elliptical beam (where the word "elliptical" refers to the form of the mirror and not to the section of the beam which is of course always circular) is therefore a divergent beam *plus* a space of convergence back of the conjugate focus; and, likewise, the hyperbolic beam is a divergent beam *minus* a space of virtual divergence between the conjugate focus and the surface of the reflector. Making the conjugate focus the origin of range length, at any given range an elliptical and hyperbolic beam may be identical in every particular, and this is what is here meant by optical equivalence. The details of the reflector design to bring about this condition will be taken up later; and, from a construction point of view, several practical distinctions will be indicated to show how two reflectors that are optically equivalent may in actual construction differ enough to make an engineering choice between things that are seemingly equal.

In the exploration of the parabolic beam the size and shape of the source was an all-important factor, while in the case of the hyperboloid and ellipsoid the form of the source is of secondary importance and the influence of the form is in the nature of a correction to the theory here outlined. These corrections apply almost solely to the edge of the beam, where the angular width of the light source is added to the natural spread of the light reflected from the surface. This leads to engineering distinctions between surfaces that are equivalent, at least for a point source. As an example, an ellipsoid and a hyperboloid of equivalent properties may be used with a spherical source which from the edge of the ellipsoid subtends two degrees, but only one degree from the edge of the hyperboloid. To the point-source width of one beam, two degrees will be added and one degree to the other. This correction is so simply made that it is not intended to do more than call attention to it; and the theory of the point-source beam can be used to give complete and accurate data on an actual beam from a spherical source, the width alone being subject to material correction.

A second practical consideration that should not be overlooked is the shadow formed by the lamp and by any opening made in the reflecting surface for the lamp base. In the ellipsoidal reflector the surface is in general smaller so that a given opening has more effect on the beam. Also, the light from the back of the lamp converges somewhat on the bulb and the bulb interference is greater than for the divergent light of the hyperboloid.

The reflectors that we use in our homes, offices, shops, and streets may nearly all be directly classified as either ellipsoidal or hyperboloidal in fundamental nature. The narrow and deep reflectors that direct light back through the lamp bulb are modified ellipsoids, while the wide and shallow reflectors that direct the light away from the lamp are modified hyperboloids. Often the modification is made for the sake of appearance or to gain a distinctive form, but this does not modify the essential nature of the reflectors.

Eccentricity and Beam of Formation

It was demonstrated in deriving equation (291) that the eccentricity e_h of a hyperboloid may be expressed in terms of the collecting angle b and the half angle of spread s. In a similar manner the ellipticity e_e of an ellipsoid may be shown to be

$$e_e = \frac{\sin b - \sin s}{\sin (b + s)} \qquad (298)$$

as compared with the ellipticity e_h for the hyperbola

$$e_h = \frac{\sin b + \sin s}{\sin (b - s)} \qquad (299)$$

The product of the two eccentricities is

$$\begin{aligned} e_e\, e_h &= \frac{\sin^2 b - \sin^2 s}{\sin^2 b \cos^2 s - \cos^2 b \sin^2 s} \\ &= \frac{\sin^2 b - \sin^2 s}{\sin^2 b - \sin^2 s - \sin^2 b \sin^2 s + \sin^2 b \sin^2 s} \\ &= 1 \qquad (300) \end{aligned}$$

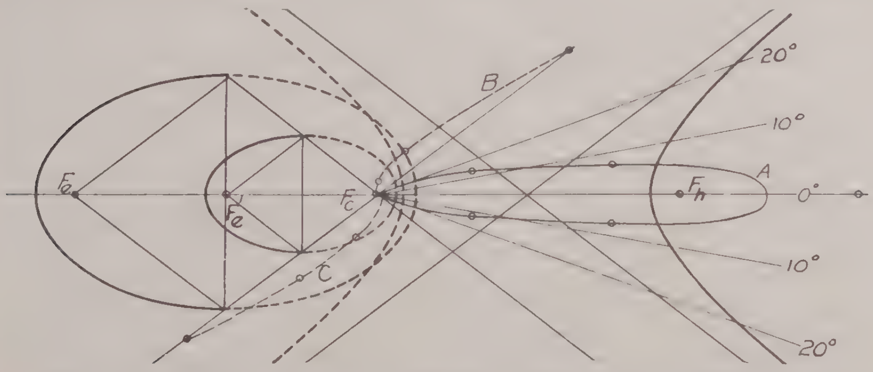


Fig. 173. Curve A is the photometric distribution of light from three surfaces—the semi-ellipsoids and the hyperboloid on the right. The focal point F_c is common to all three and is the radiating point for the three identical beams. Photometric curve B is the distribution (to an enlarged scale) of light from the dotted ellipsoids, while photometric curve C is the distribution of light from the dotted hyperboloid. In both cases the sum of the angular widths of the beam equals 360 deg., but the beams from the two branches of the hyperboloid overlap and do not cover a complete circle

This shows that for a given ray radiated at an angle b from the axis there is a pair of conics having reciprocal values of e that will reflect the ray at the same angle. From this it is evident that the beam will be identical throughout, for we may take two identical zones of radiated light bounded by the angles b and $b+db$ (which angles of course include equal quantities of light) and project these zones into identical beam zones bounded by the angles s and $s+ds$. The beam zones, being equal in size and in quantity of light included, must give identical beam intensities.

For a point source this identity of beam is wholly independent of the actual size of the reflector, as is indicated by the absence of any factor of magnitude or scale (such as m or n) in equation (300).

Equivalent Reflectors of Equal Interfocal Distance

The distance between the focii of a hyperboloid is

$$d_h = 2m_h e_h \qquad (301)$$

where m_h and e_h are the semi-major axis and eccentricity respectively.

Similarly

$$d_e = 2m_e e_e \qquad (302)$$

expresses the inter-focal distance of an ellipsoid of major axis $2m_e$ and eccentricity e_e. Equating (301) and (302) there results:

$$\frac{m_e}{m_h} = \frac{e_h}{e_e} \qquad (303)$$

or, the major axes of equivalent curves having equal inter-focal distances are in inverse proportion as the eccentricities. Thus for eccentricities of 1.25 and 0.80 the major axes are in the proportion of 0.80 to 1.25.

Equivalent Reflectors of Equal Focal Length

The focal length of the adjacent branch of a hyperboloid is

$$F_h = m_h\,(e_h - 1) \qquad (304)$$

while for the adjacent half of an ellipsoid

$$F_e = m_e(1 - e_e) \qquad (305)$$

Setting $F_h = F_e$ there results:

$$\frac{m_h}{m_e} = \frac{1 - e_e}{e_h - 1} \qquad (306)$$

which is the condition for equal focal lengths in optically equivalent curves. It often happens that the size of a lamp bulb, or the mechanism of an arc lamp sets a lower limit to the focal length, which thus becomes a fixed quantity for a given lamp.

Equivalent Reflectors of Equal Diameter

The diameter of an ellipsoid is

$$D_e = \frac{2m_e\,(1 - e^2_e) \sin b}{1 + e_e \cos b} \qquad (307)$$

while for a hyperboloid

$$D_h = \frac{2m_h\,(e^2_h - 1) \sin b}{1 + e_h \cos b} \qquad (308)$$

Setting these two expressions equal we get

$$\frac{m_e}{m_h} = \frac{(e^2_h - 1)\,(1 + e_e \cos b)}{(1 - e^2_e)\,(1 + e_h \cos b)} \qquad (309)$$

This condition of equal diameters is of practical importance in designing different reflecting surfaces to go into the same holder or housing.

Equivalent Reflectors of Equal Depth

The depth of an ellipsoid is

$$x_e = m_e\,(1-e_e) - \frac{m_e\,(1-e^2_e)\cos b}{1+e_e\cos b} \qquad (310)$$

while the depth of a hyperboloid is

$$x_h = m_h\,(e_h-1) - \frac{m_h\,(e^2_h-1)\cos b}{1+e_h\cos b} \qquad (311)$$

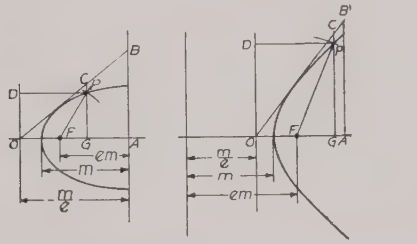


Fig. 174. Given m, the semi-major axis and the eccentricity e, the directrix is located at a distance $\frac{m}{e}$ from the minor axis and parallel to it. The focal point is distant em from the same axis. Draw a line parallel to the directrix at any distance (DP) and note where it is intersected by an arc about the focus at radius e (DP); the point of intersection is a point on the curve

Setting equations (310) and (311) equal, the major axes are in the proportion

$$\frac{m_h}{m_e} = \frac{e_h - 1 - \dfrac{(e^2_h-1)\cos b}{1+e_h\cos b}}{1-e_e - \dfrac{(1-e^2_e)\cos b}{1+e_e\cos b}} \qquad (312)$$

The size of lamp bulb is one of the determining factors in many reflectors as often the focal length is made as small as will accommodate the lamp. The bulb sometimes plays an important part in this type of beam where each section of reflecting surface contributes light to a limited area of the beam. Any obstruction in the beam leads to a dark area, and the hyperboloidal beam is less influenced than the ellipsoidal beam on account of the reflected light being diverged from the bulb rather than concentrated upon it.

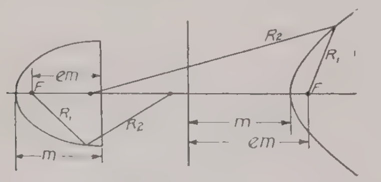


Fig. 175. Given e the eccentricity and m the semi-major axis, the ellipse may be constructed by noting the intersection of arcs of radius R about one focus and radius $2m-R$ about the conjugate focus. The construction of the hyperbola is the same except that one radius is R and the other is $2M+R$

DESIGN EQUATIONS FOR ELLIPSOIDS AND HYPERBOLOIDS

The groups of equations that follow were arranged for the convenient use of the reflector designer, who commonly starts with two or three known or desired conditions and must solve for the remaining factors in order to determine the surface.

The following symbols are used:

b = generating angle, from vertex to edge of reflector.
e = eccentricity of generating curve.
F_1 = axial distance from focal point to adjacent surface.
F_2 = axial distance from focal point to opposite surface.
m = semi-major axis.
n = semi-minor axis.
s = half angle of beam width, with a point source.
x = distance from vertex to plane of edge of reflector.

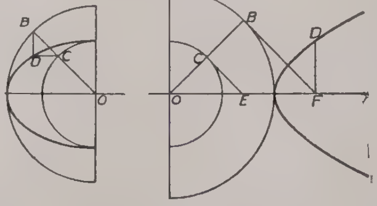


Fig. 176. Given the semi-major and semi-minor axes, construct two concentric circles with these values for radii. To determine an ellipse draw any radius OCB. At the intersection with the minor circle draw a line parallel to the major axis, and at the intersection with the major circle draw a line parallel to the minor axis. The intersection of these two lines is a point on the ellipse. The hyperbola is constructed by drawing tangents at the points of intersection C and B and noting the intersections E and F at the lines with the major axis. At the point F erect a perpendicular (FD) equal to (CE) and the point D will be on the hyperbola

y = radius to point on edge of reflector.
R_1 = the radius vector to the adjacent surface.
R_2 = the radius vector to the opposite surface.

In the equations where a combined plus-and-minus sign occur, the **upper** sign is used in solving for an **ellipse**, and the *lower* in solving for a *hyperbola*.

Throughout the various groups of equations the three given quantities are arranged alphabetically at the head of each group so that reference to them may be made as if they were three-letter words in a dictionary.

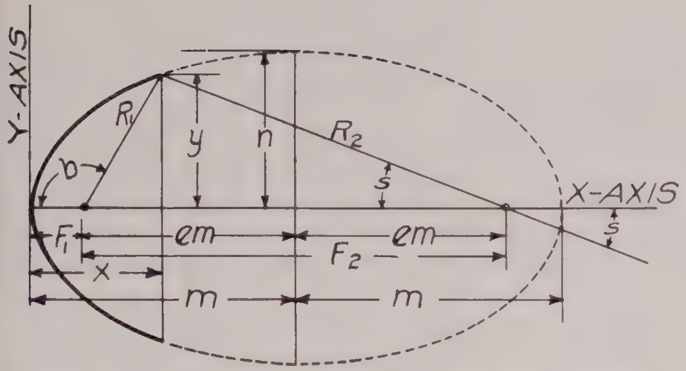


Fig. 177. This figure is to be used in connection with the groups of equations that follow

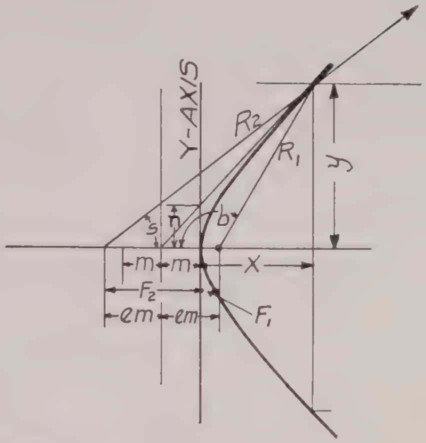


Fig. 178. This figure is to be used in connection with the groups of equations that follow

b, e, F₁

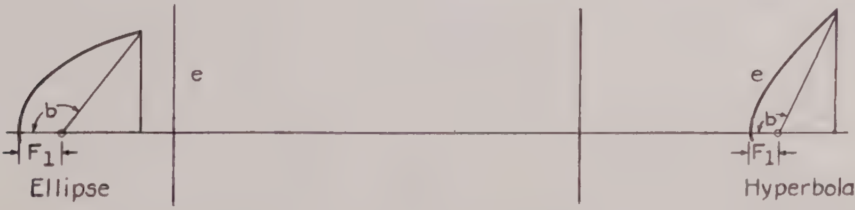


Fig. 179

$$m = \frac{\mp F_1}{e-1} \ldots\ldots\ldots\ldots (313)$$

$$n = m\sqrt{\mp (e^2-1)} \ldots\ldots (314)$$

$$F_2 = \mp F_1 + 2m \ldots\ldots\ldots\ldots (315)$$

$$y = \frac{\mp m\,(e^2-1)\sin b}{1+e\cos b} \ldots\ldots (316)$$

$$x = F_1\left(\frac{1-\cos b}{1+e\cos b}\right) \ldots (317)$$

$$\tan s = \frac{y}{F_2 \mp x} \ldots\ldots\ldots\ldots (318)$$

b, e, m

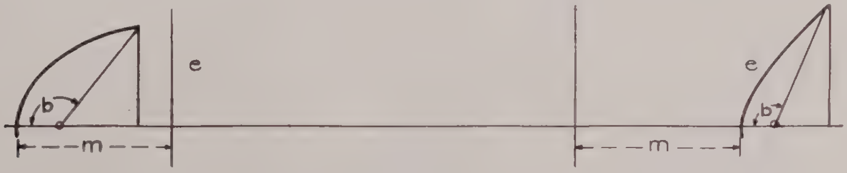


Fig. 180

$$n = m\sqrt{\mp (e^2-1)} \ldots\ldots (314)$$

$$F_1 = \mp m\,(e-1) \ldots\ldots\ldots\ldots (319)$$

$$F_2 = m\,(e+1) \ldots\ldots\ldots\ldots (320)$$

$$y = \frac{\mp m\,(e^2-1)\sin b}{1+e\cos b} \ldots\ldots (316)$$

$$x = F_1\left(\frac{1-\cos b}{1+e\cos b}\right) \ldots (317)$$

$$\tan s = \frac{y}{F_2 \mp x} \ldots\ldots\ldots\ldots (318)$$

b, e, x

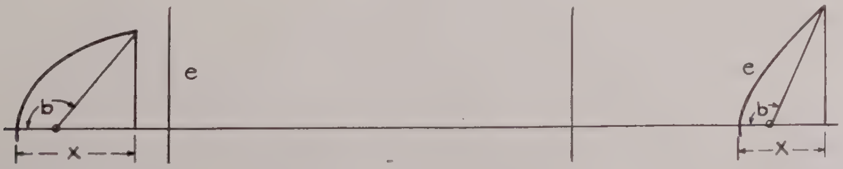


Fig. 181

$$m = \mp \frac{x\,(1+e\cos b)}{(e-1)\,(1-\cos b)} \ldots (321)$$

$$n = m\sqrt{\mp (e^2-1)} \ldots\ldots (314)$$

$$F_1 = \mp m\,(e-1) \ldots\ldots\ldots\ldots (319)$$

$$F_2 = m\,(e+1) \ldots\ldots\ldots\ldots (320)$$

$$y = \frac{\mp m\,(e^2-1)\sin b}{1+e\cos b} \ldots (316)$$

$$\tan s = \frac{y}{F_2 \mp x} \ldots\ldots\ldots\ldots (318)$$

Where the double sign ± and ∓ appear, the upper sign is to be used for an ellipse and the lower for a hyperbola.

b, e, y

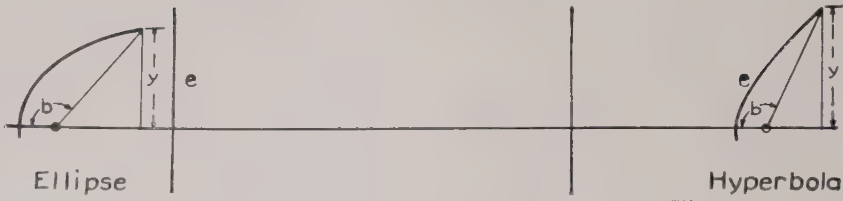


Fig. 182

$$m = \mp\frac{y\,(1+e\cos b)}{(e^2-1)\sin b}\ldots\ldots(322) \qquad F_1 = \mp m\,(e-1)\ldots\ldots\ldots\ldots(319) \qquad x = F_1\left(\frac{1-\cos b}{1+e\cos b}\right)\ldots(317)$$

$$n = m\sqrt{\mp(e^2-1)}\ldots\ldots\ldots(314) \qquad F_2 = m\,(e+1)\ldots\ldots\ldots\ldots(320) \qquad \tan s = \frac{y}{F_2 \mp x}\ldots\ldots\ldots\ldots(318)$$

b, F₁, m

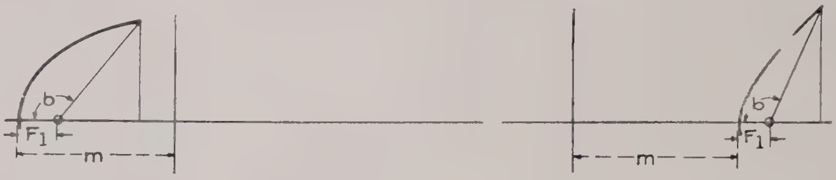


Fig. 183

$$e = 1 \mp \frac{F_1}{m}\ldots\ldots\ldots\ldots\ldots(323) \qquad F_2 = \mp F_1 + 2m\ldots\ldots\ldots\ldots(315) \qquad x = F_1\left(\frac{1-\cos b}{1+e\cos b}\right)\ldots(317)$$

$$n = m\sqrt{\mp(e^2-1)}\ldots\ldots\ldots(314) \qquad y = \frac{\mp m\,(e^2-1)\sin b}{1+e\cos b}\ldots\ldots(316) \qquad \tan s = \frac{y}{F_2 \mp x}\ldots\ldots\ldots\ldots(318)$$

b, F₁, s

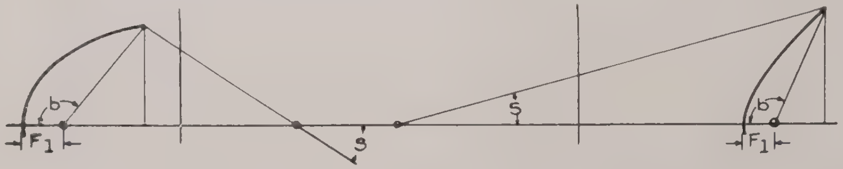


Fig. 184

$$e = \frac{\sin b \mp \sin s}{\sin\,(b \pm s)}\ldots\ldots\ldots(324) \qquad n = m\sqrt{\mp(e^2-1)}\ldots\ldots\ldots(314) \qquad y = \frac{\mp m\,(e^2-1)\sin b}{1+e\cos b}\ldots\ldots(316)$$

$$m = \frac{\mp F_1}{e-1}\ldots\ldots\ldots\ldots\ldots(313) \qquad F_2 = \mp F_1 + 2m\ldots\ldots\ldots\ldots(315) \qquad x = F_1\left(\frac{1-\cos b}{1+e\cos b}\right)\ldots\ldots(317)$$

b, F₁, x

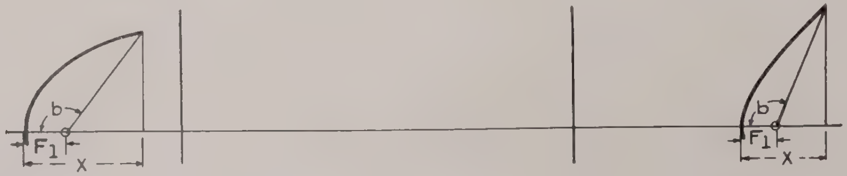


Fig. 185

$$e = \frac{F_1\,(1-\cos b)-x}{x\cos b}\ldots\ldots(325) \qquad n = m\sqrt{\mp(e^2-1)}\ldots\ldots\ldots(314) \qquad y = \frac{\mp m\,(e^2-1)\sin b}{1+e\cos b}\ldots(316)$$

$$m = \frac{\mp F_1}{e-1}\ldots\ldots\ldots\ldots\ldots(313) \qquad F_2 = \mp F_1 + 2m\ldots\ldots\ldots\ldots(315) \qquad \tan s = \frac{y}{F_2 \mp x}\ldots\ldots\ldots\ldots(318)$$

b, F₁, y

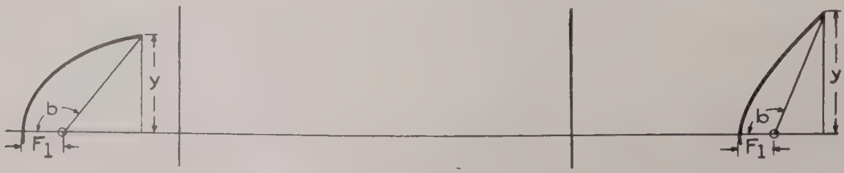


Fig. 186

$$e = \frac{F_1\sin b - y}{y\cos b - F_1\sin b}\ldots\ldots(326) \qquad n = m\sqrt{\mp(e^2-1)}\ldots\ldots\ldots(314) \qquad x = F_1\left(\frac{1-\cos b}{1+e\cos b}\right)\ldots(317)$$

$$m = \frac{\mp F_1}{e-1}\ldots\ldots\ldots\ldots\ldots(313) \qquad F_2 = m\,(e+1)\ldots\ldots\ldots\ldots(320) \qquad \tan s = \frac{y}{F_2 \mp x}\ldots\ldots\ldots\ldots(318)$$

Where the double signs ± and ∓ appear, the upper sign is to be used for an ellipse and the lower for a hyperbola.

b, m, s

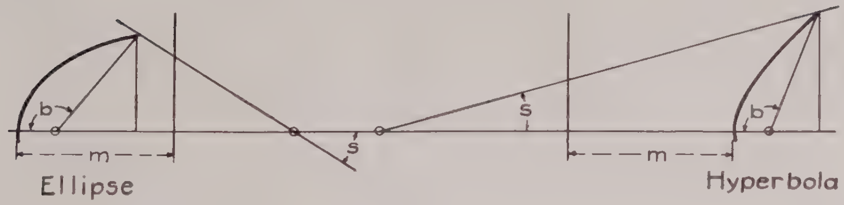


Fig. 187

$$e = \frac{\sin b \mp \sin s}{\sin (b \pm s)} \tag{324}$$
$$F_1 = \mp m\ (e-1) \tag{319}$$
$$y = \frac{\mp m\ (e^2-1) \sin b}{1+e \cos b} \tag{316}$$
$$n = m\sqrt{\mp(e^2-1)} \tag{314}$$
$$F_2 = m\ (e+1) \tag{320}$$
$$x = F_1 \left(\frac{1-\cos b}{1+e \cos b} \right) \tag{317}$$

b, m, x

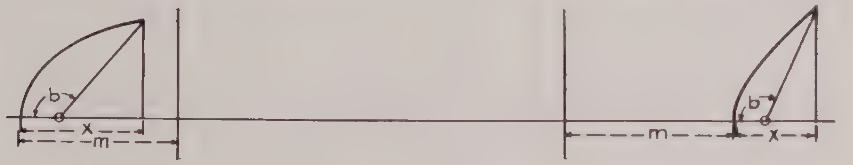


Fig. 188

$$e = \frac{m\ (1-\cos b) \mp x}{m\ (1-\cos b) \pm x \cos b} \tag{327}$$
$$F_1 = \mp m\ (e-1) \tag{319}$$
$$y = \frac{\mp m\ (e^2-1) \sin b}{1+e \cos b} \tag{316}$$
$$n = m\sqrt{\mp(e^2-1)} \tag{314}$$
$$F_2 = m\ (e+1) \tag{320}$$
$$\tan s = \frac{y}{F_2 \mp x} \tag{318}$$

b, m, y

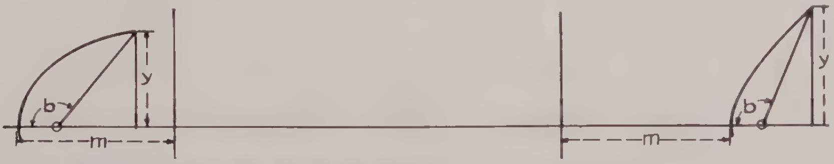


Fig. 189

$$e = \frac{\mp y \cos b + \sqrt{y^2 \cos^2 b \mp 4\ y\ m \sin b + 4\ m^2 \sin^2 b}}{2\ m \sin b} \tag{328}$$
$$x = F_1 \left(\frac{1-\cos b}{1+e \cos b} \right) \tag{317}$$
$$n = m\sqrt{\mp(e^2-1)} \tag{314}$$
$$F_1 = \mp m\ (e-1) \tag{319}$$
$$F_2 = m\ (e+1) \tag{320}$$
$$\tan s = \frac{y}{F_2 \mp x} \tag{318}$$

b, s, x

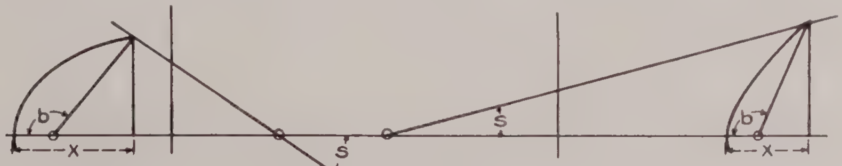


Fig. 190

$$e = \frac{\sin b \mp \sin s}{\sin (b \pm s)} \tag{324}$$
$$m = \frac{\mp F_1}{e-1} \tag{313}$$
$$F_2 = \mp F_1 + 2m \tag{315}$$
$$F_1 = \frac{x\ (1+e \cos b)}{1-\cos b} \tag{329}$$
$$n = m\sqrt{\mp(e^2-1)} \tag{314}$$
$$y = \frac{\mp m\ (e^2-1) \sin b}{1+e \cos b} \tag{316}$$

b, s, y

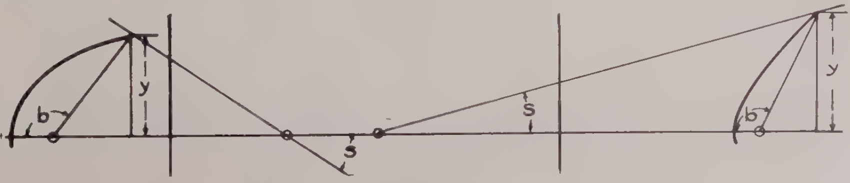


Fig. 191

$$e = \frac{\sin b \mp \sin s}{\sin (b \pm s)} \tag{324}$$
$$n = m\sqrt{\mp(e^2-1)} \tag{314}$$
$$F_2 = m\ (e+1) \tag{320}$$
$$m = \mp \frac{y\ (1+e \cos b)}{(e^2-1) \sin b} \tag{322}$$
$$F_1 = \mp m\ (e-1) \tag{319}$$
$$x = F_1 \left(\frac{1-\cos b}{1+e \cos b} \right) \tag{317}$$

Where the double signs ± and ∓ appear, the upper sign is to be used for an ellipse and the lower for a hyperbola.

b, x, y

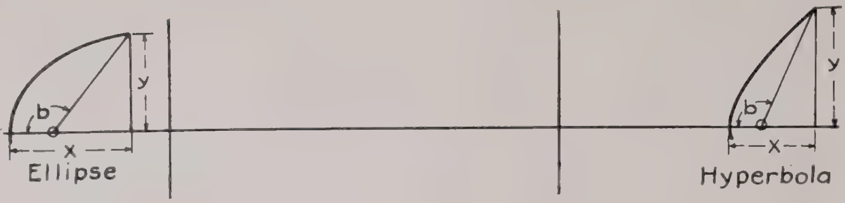


Fig. 192

$$F_1=\frac{x\tan b+y}{\tan b}\tag{330}$$

$$e=\frac{F_1\sin b-y}{y\cos b-F_1\sin b}\tag{326}$$

$$m=\frac{\mp F_1}{e-1}\tag{313}$$

$$n=m\sqrt{\mp(e^2-1)}\tag{314}$$

$$F_2=\mp F_1+2m\tag{315}$$

$$\tan s=\frac{y}{F_2\mp x}\tag{318}$$

e, F₁, s

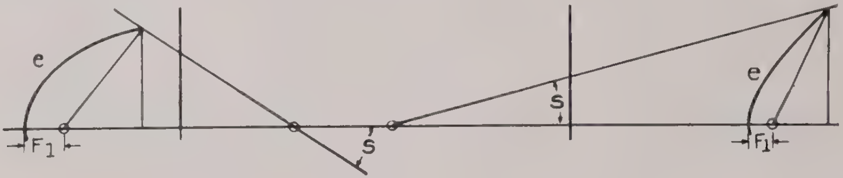


Fig. 193

$$m=\frac{\mp F_1}{e-1}\tag{313}$$

$$n=m\sqrt{\mp(e^2-1)}\tag{314}$$

$$F_2=\mp F_1+2m\tag{315}$$

$$R_2=-\frac{m\,(e^2-1)}{1-e\cos s}\tag{331}$$

$$R_1=\mp(R_2-2m)\tag{332}$$

$$y=R_2\sin s\tag{333}$$

$$x=\mp(R_2\cos s-F_2)\tag{334}$$

$$\sin b=\frac{y}{R_1}\tag{335}$$

e, F₁, x

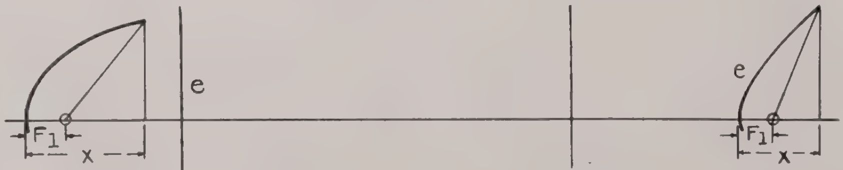


Fig. 194

$$\cos b=\frac{F_1-x}{F_1+ex}\tag{336}$$

$$m=\frac{\mp F_1}{e-1}\tag{313}$$

$$n=m\sqrt{\mp(e^2-1)}\tag{314}$$

$$F_2=\mp F_1+2m\tag{315}$$

$$y=\frac{\mp m\,(e^2-1)\sin b}{1+e\cos b}\tag{316}$$

$$\tan s=\frac{y}{F_2\mp x}\tag{318}$$

e, F₁, y

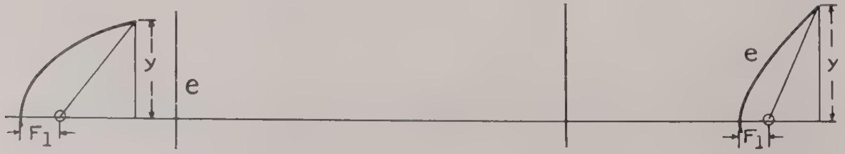


Fig. 195

$$m=\frac{\mp F_1}{e-1}\tag{313}$$

$$n=m\sqrt{\mp(e^2-1)}\tag{314}$$

$$F_2=\mp F_1+2m\tag{315}$$

$$x=\pm m\mp m\sqrt{1\mp\frac{y^2}{n^2}}\tag{337}$$

$$\cos b=\frac{F_1-x}{F_1+ex}\tag{336}$$

$$\tan s=\frac{y}{F_2\mp x}\tag{318}$$

e, m, s

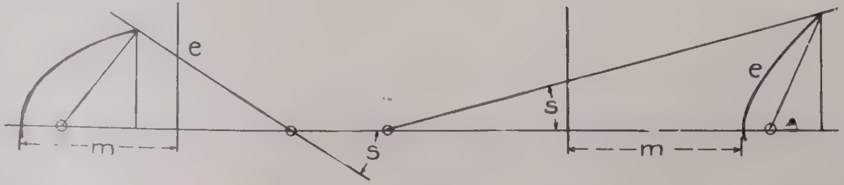


Fig. 196

$$n=m\sqrt{\mp(e^2-1)}\tag{314}$$

$$F_1=\mp m\,(e-1)\tag{319}$$

$$F_2=m\,(e+1)\tag{320}$$

$$R_2=-\frac{m\,(e^2-1)}{1-e\cos s}\tag{331}$$

$$R_1=\mp(R_2-2m)\tag{332}$$

$$y=R_2\sin s\tag{333}$$

$$x=\mp(R_2\cos s-F_2)\tag{334}$$

$$\sin b=\frac{y}{R_1}\tag{335}$$

Where the double signs ± and ∓ appear, the upper sign is to be used for an ellipse and the lower for a hyperbola.

e, m, x

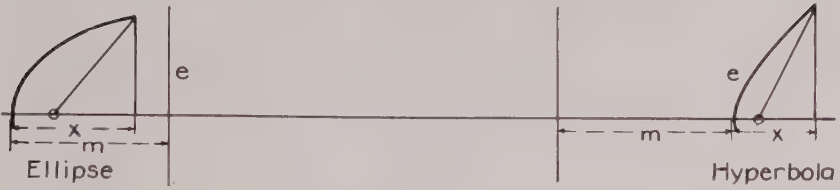


Fig. 197

$n=m\sqrt{\mp(e^2-1)}$ ......(314)

$F_1=\mp m\ (e-1)$ ....(319)

$y=\dfrac{\mp m\ (e^2-1)\sin b}{1+e\cos b}$ ..(316)

$\cos b=\dfrac{\mp m\ (e-1)-x}{\mp m\ (e-1)+ex}$ ....(338)

$F_2=m\ (e+1)$ ....(320)

$\tan s=\dfrac{y}{F_2\mp x}$ ....(318)

e, m, y

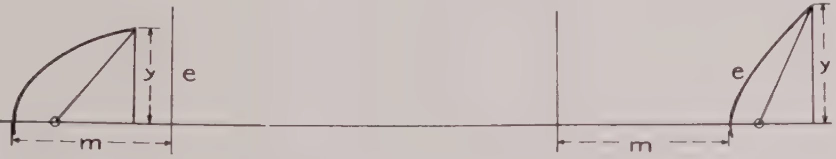


Fig. 198

$F_1=\mp m\ (e-1)$ ....(319)

$n=m\sqrt{\mp(e^2-1)}$ ....(314)

$\cos b=\dfrac{F_1-x}{F_1+ex}$ ....(336)

$F_2=m\ (e+1)$ ....(320)

$x=\pm m\mp m\sqrt{1\mp\dfrac{y^2}{n^2}}$ ......(337)

$\tan s=\dfrac{y}{F_2\mp x}$ ....(318)

e, s, x

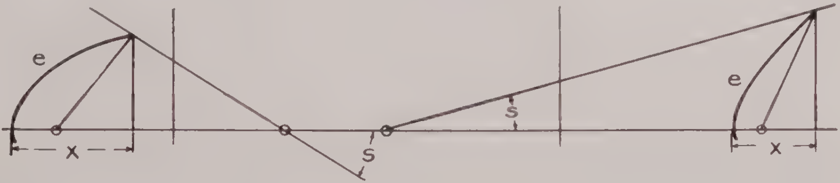


Fig. 199

$m=\mp\dfrac{x\ (e\cos s-1)}{(e+1)\ (1-\cos s)}$ ....(339)

$F_1=\mp m\ (e-1)$ ....(319)

$\cos b=\dfrac{F_1-x}{F_1+ex}$ ....(336)

$n=m\sqrt{\mp(e^2-1)}$ ....(314)

$F_2=m\ (e+1)$ ....(320)

$y=\dfrac{\mp m\ (e^2-1)\sin b}{1+e\cos b}$ ..(316)

e, s, y

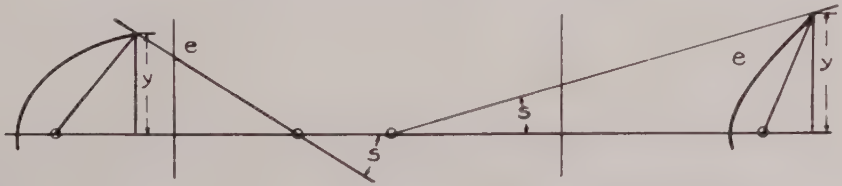


Fig. 200

$m=-\dfrac{y\ (1-e\cos s)}{(e^2-1)\sin s}$ ......(340)

$F_1=\mp m\ (e-1)$ ....(319)

$F_2=m\ (e+1)$ ....(320)

$R_1=\mp(R_2-2m)$ ....(332)

$x=\mp(R_2\cos s-F_2)$ ...(334)

$n=m\sqrt{\mp(e^2-1)}$ ....(314)

$R_2=-\dfrac{m\ (e^2-1)}{1-e\cos s}$ ....(331)

$\cos b=\dfrac{\mp m\ (e^2-1)-R_1}{e\,R_1}$ ...(341)

e, x, y

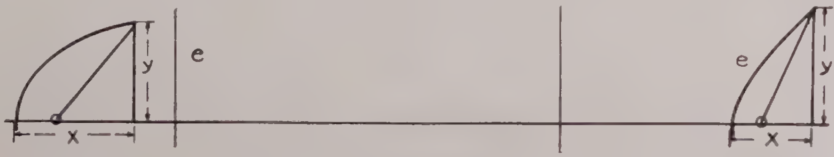


Fig. 201

$\cos b=\dfrac{\left(\dfrac{y}{x}\right)^2-(e+1)^2}{\left(\dfrac{y}{x}\right)^2+(e+1)^2}$ ....(342)

$m=\mp\dfrac{x\ (1+e\cos b)}{(e-1)\ (1-\cos b)}$ ...(321)

$F_1=\mp m\ (e-1)$ ....(319)

$F_2=m\ (e+1)$ ....(320)

$n=m\sqrt{\mp(e^2-1)}$ ....(314)

$\tan s=\dfrac{y}{F_2\mp x}$ ....(318)

Where the double signs ± and ∓ appear, the upper sign is to be used for an ellipse and the lower for a hyperbola.

F_1, m, s

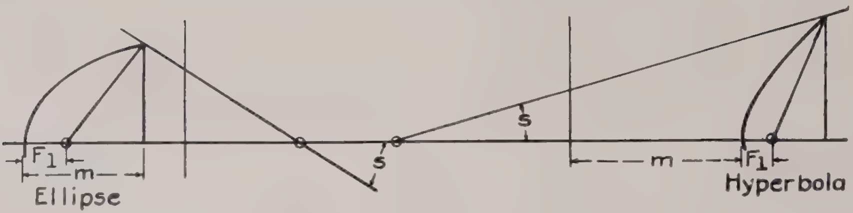


Fig. 202

$$e = 1 \mp \frac{F_1}{m} \quad \ldots\ldots (323)$$

$$n = m\sqrt{\mp(e^2-1)} \quad \ldots\ldots (314)$$

$$F_2 = \mp F_1 + 2m \quad \ldots\ldots (315)$$

$$R_2 = -\frac{m\,(e^2-1)}{1-e\cos s} \quad \ldots\ldots (331)$$

$$R_1 = \mp(R_2 - 2m) \quad \ldots\ldots (332)$$

$$y = R_2 \sin s \quad \ldots\ldots (333)$$

$$x = \mp(R_2 \cos s - F_2) \quad \ldots\ldots (334)$$

$$\sin b = \frac{y}{R_1} \quad \ldots\ldots (335)$$

F_1, m, x

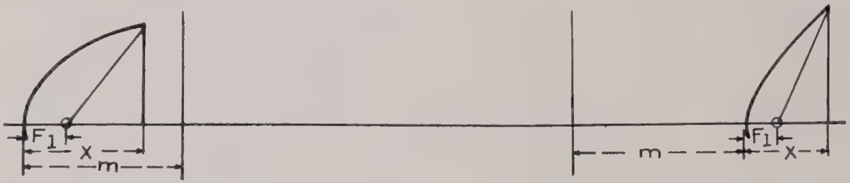


Fig. 203

$$e = 1 \mp \frac{F_1}{m} \quad \ldots\ldots (323)$$

$$n = m\sqrt{\mp(e^2-1)} \quad \ldots\ldots (314)$$

$$\cos b = \frac{F_1 - x}{F_1 + ex} \quad \ldots\ldots (336)$$

$$F_2 = \mp F_1 + 2m \quad \ldots\ldots (315)$$

$$y = \frac{\mp m\,(e^2-1)\sin b}{1 + e\cos b} \quad \ldots\ldots (316)$$

$$\tan s = \frac{y}{F_2 \mp x} \quad \ldots\ldots (318)$$

F_1, m, y

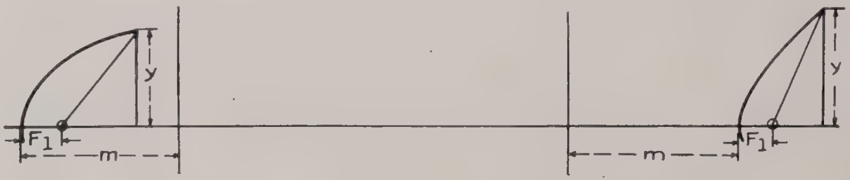


Fig. 204

$$e = 1 \mp \frac{F_1}{m} \quad \ldots\ldots (323)$$

$$F_2 = m\,(e+1) \quad \ldots\ldots (320)$$

$$n = m\sqrt{\mp(e^2-1)} \quad \ldots\ldots (314)$$

$$x = \pm m \mp m\sqrt{1 \mp \frac{y^2}{n^2}} \quad \ldots\ldots (337)$$

$$\cos b = \frac{F_1 - x}{F_1 + ex} \quad \ldots\ldots (336)$$

$$\tan s = \frac{y}{F_2 \mp x} \quad \ldots\ldots (318)$$

F_1, s, x

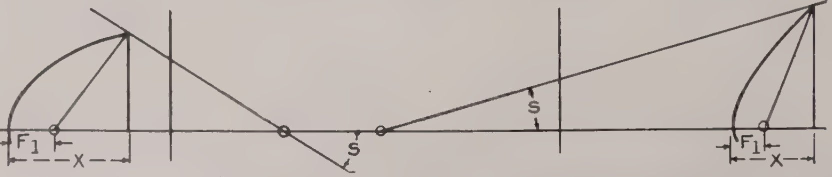


Fig. 205

$$e = \frac{x\,(1+\cos s) + F_1(1-\cos s) \mp \sqrt{[x\,(1+\cos s) + F_1\,(1-\cos s)]^2 - 4x\,(x - F_1 + F_1\cos s)\cos s}}{2\,x\cos s} \quad \ldots\ldots (343)$$

$$m = \frac{\mp F_1}{e-1} \quad \ldots\ldots (313)$$

$$n = m\sqrt{\mp(e^2-1)} \quad \ldots\ldots (314)$$

$$F_2 = \mp F_1 + 2m \quad \ldots\ldots (315)$$

$$\cos b = \frac{F_1 - x}{F_1 + ex} \quad \ldots\ldots (336)$$

$$y = \frac{\mp m\,(e^2-1)\sin b}{1 + e\cos b} \quad \ldots\ldots (316)$$

F_1, s, y

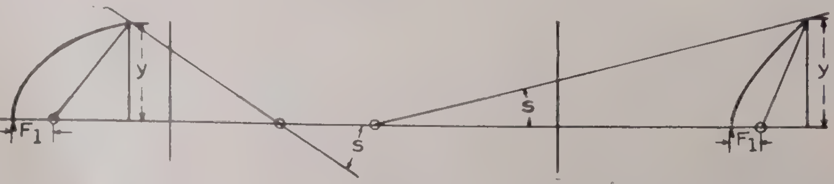


Fig. 206

$$e = \frac{y \mp F_1 \sin s}{y\cos s \pm F_1 \sin s} \quad \ldots\ldots (344)$$

$$m = \frac{\mp F_1}{e-1} \quad \ldots\ldots (313)$$

$$n = m\sqrt{\mp(e^2-1)} \quad \ldots\ldots (314)$$

$$F_2 = \mp F_1 + 2m \quad \ldots\ldots (315)$$

$$R_2 = -\frac{m(e^2-1)}{1-e\cos s} \quad \ldots\ldots (331)$$

$$R_1 = \mp(R_2 - 2m) \quad \ldots\ldots (332)$$

$$x = \mp(R_2 \cos s - F_2) \quad \ldots\ldots (334)$$

$$\sin b = \frac{y}{R_1} \quad \ldots\ldots (335)$$

Where the double signs ± and ∓ appear, the upper sign is to be used for an ellipse and the lower for a hyperbola.

F₁, x, y

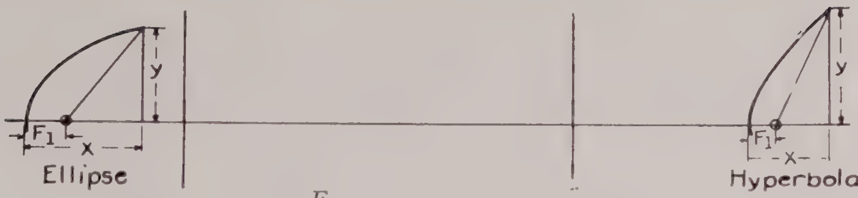


Fig. 207

$$\tan b = \frac{y}{F_1 - x} \tag{345}$$

$$e = \frac{F_1 \sin b - y}{y \cos b - F_1 \sin b} \tag{326}$$

$$m = \frac{\mp F_1}{e-1} \tag{313}$$

$$n = m\sqrt{\mp(e^2-1)} \tag{314}$$

$$F_2 = \mp F_1 + 2m \tag{315}$$

$$\tan s = \frac{y}{F_2 \mp x} \tag{318}$$

m, s, x

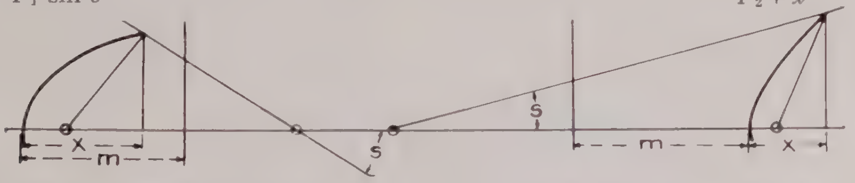


Fig. 208

$$e = \frac{x \mp m\,(1-\cos s)}{x \cos s \pm m\,(1-\cos s)} \tag{346}$$

$$n = m\sqrt{\mp(e^2-1)} \tag{314}$$

$$F_1 = \mp m\,(e-1) \tag{319}$$

$$F_2 = m\,(e+1) \tag{320}$$

$$\cos b = \frac{F_1 - x}{F_1 + ex} \tag{336}$$

$$y = \frac{\mp m\,(e^2-1) \sin b}{1 + e \cos b} \tag{316}$$

m, s, y

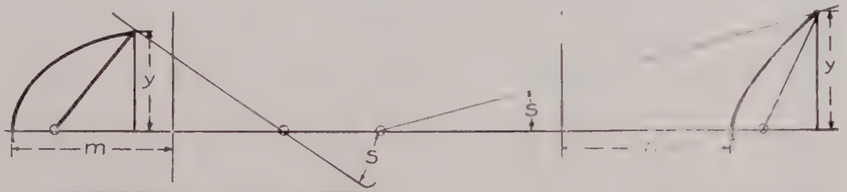


Fig. 209

$$e = \frac{y \cos s \mp \sqrt{y^2 \cos^2 s - 4\,my \sin s + 4m^2 \sin^2 s}}{2\,m \sin s} \tag{347}$$

$$n = m\sqrt{\mp(e^2-1)} \tag{314}$$

$$F_1 = \mp m\,(e-1) \tag{319}$$

$$F_2 = m\,(e+1) \tag{320}$$

$$R_2 = -\frac{m\,(e^2-1)}{1 - e \cos s} \tag{331}$$

$$R_1 = \mp(R_2 - 2m) \tag{332}$$

$$\cos b = \frac{\mp m\,(e^2-1) - R_1}{e\,R_1} \tag{341}$$

$$x = F_1 - R_1 \cos b \tag{348}$$

m, x, y

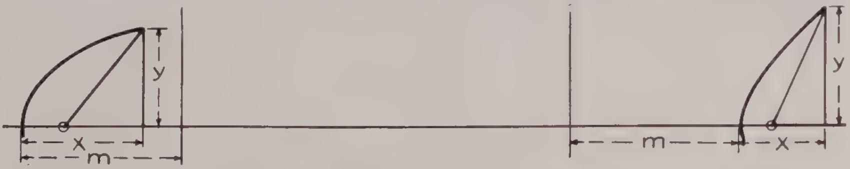


Fig. 210

$$n = \frac{y}{\sqrt{\pm 1 \mp \left(\frac{m \mp x}{m}\right)^2}} \tag{349}$$

$$e = \frac{\sqrt{m^2 \mp n^2}}{m} \tag{350}$$

$$F_1 = \mp m\,(e-1) \tag{319}$$

$$F_2 = m\,(e+1) \tag{320}$$

$$\tan s = \frac{y}{F_2 \mp x} \tag{318}$$

$$\tan b = \frac{y}{F_1 - x} \tag{345}$$

s, x, y

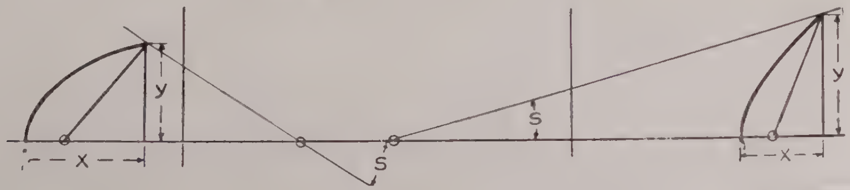


Fig. 211

$$F_2 = y \cot s \pm x \tag{351}$$

$$R_2 = \frac{F_2 \mp x}{\cos s} \tag{352}$$

$$e = \frac{R_2 - F_2}{R_2 \cos s - F_2} \tag{353}$$

$$m = \frac{F_2}{e+1} \tag{354}$$

$$n = m\sqrt{\mp(e^2-1)} \tag{314}$$

$$F_1 = \mp(F_2 - 2m) \tag{355}$$

$$R_1 = \mp(R_2 - 2m) \tag{356}$$

$$\tan b = \frac{y}{F_1 - x} \tag{345}$$

Where the double signs ± and ∓ appear, the upper sign is to be used for an ellipse and the lower for a hyperbola.

The Charles A. Coffin Foundation Award to the Consumers Power Company of Jackson, Mich.

The gold medal award of the Charles A. Coffin Foundation to the public service company in the United States, which during the year 1924 made the most distinguished contribution to the development of electric light and power service for the benefit of the American people, was announced on June 17th, at the annual convention of the National Electric Light Association, by Franklin T. Griffith, as chairman of the Association's Charles A. Coffin prize committee. The recipient was the Consumers Power Company of Jackson, Michigan.

Obverse and Reverse of the Charles A. Coffin Foundation Gold Medal Awarded to the Consumers Power Company of Michigan

This is the third annual award of the Medal made available through the creation of the Charles A. Coffin Foundation by the General Electric Company in 1922. With the Medal goes the sum of $1000, to be applied by the recipient to its Employees' Benefit Association or similar organization. In the two years past the Medal has been awarded to the Southern California Edison Company and to the Public Service Company of Northern Illinois.

The Consumers Power Company now serves more than 170 communities and its customers are in excess of 200,000, which, according to Mr. Griffith, represents a growth of more than 11 per cent over the preceding year. Eighty-seven per cent of the homes in the Company's territory are now electrified.

During 1924 this company concluded a home survey, its representatives visiting more than 167,000 customers. Of this number, 98.4 per cent expressed satisfaction with the service rendered, a decrease of 57 per cent in the number of complaints over 1923.

In 1924 also, the company added 244 miles of transmission lines and five new substations to its plant. In the campaign for customer ownership a gain of 55 per cent over the past year was made, so that there is at present a total of 17,966 customer stockholders. In addition, the company has increased the number of its employees holding stock by more than 23 per cent.

In its illuminating gas service department, the Consumers Power Company supplied more than 94,000 customers in 15 communities, the daily capacity of the total gas plant being in excess of 25,000,000 cu. ft.

"In practically every field," declared Mr. Griffith, "this company has shown a consistently progressive method and policy, and the results can be called outstanding in every sense of the word."

In Memoriam: Tracy E. Bibbins

Tracy Elwood Bibbins, born in San Francisco, September 12, 1866, died Friday evening, July 3rd, at his home in Berkeley, California. A "self-made man," he rose from modest circumstances to the presidency of one of the Pacific Coast's large electrical supply companies.

After engaging in various occupations as a young man, he obtained work in the construction department of one of the early electric street car systems in Portland, Oregon. This was his advent into the electrical business.

Shortly after this—in October, 1889—he accepted a position in the Warehouse Department of the Edison Electric Illuminating Company of Portland. Being adept in his work as well as industrious and persevering, he was soon advanced to a position in the Supply Department.

As a result of various consolidations, the Edison Electric Illuminating Company became the Edison General Electric Company, and in turn the General Electric Company was formed. Mr. Bibbins continued with the various consolidated organizations, and in 1894 was transferred to San Francisco to continue his work in the Supply Department under Dr. Thomas Addison. In 1901, Dr. Addison, in recognition of his loyalty and ability, appointed him manager of the Supply Department, and in 1910 advanced him to the position of Assistant Manager of the San Francisco Office of the General Electric Company. Mr. Bibbins' ability as an executive resulted in his being appointed manager of the San Francisco Office in 1912, and as a result of his foresight and the part he took in the formation of the Pacific States Electric Company, he became president of that organization in September, 1916, after having been on the board of directors for several years.

Mr. Bibbins was one of the founders of the San Francisco Electrical Development League of which he was president in 1913. He was a director in the Pacific National Bank of San Francisco, a prominent Mason, and a member of numerous clubs in and about the western metropolis.

TRACY ELWOOD BIBBINS

He was married in San Francisco on October 30, 1895, to Adele Grant, formerly of Portland. They had two daughters, Mrs. J. D. Burns and Mrs. H. Q. Noack.

Mr. Bibbins' fine characteristics were evidenced in the development of a beautiful home life as much as they were in business. It was this versatility that no doubt won for him the enviable position he occupied among his many personal friends and makes his passing a great loss not only to his family, but to his many associates both in and out of the electrical business.

His absence will be definitely felt, in the east, as well as on the Pacific Coast, in the industry to which he contributed so much. He was one of the outstanding and constructive figures of this industry.

What damages an Arrester?

Heat—a function of Current and Time

Any good arrester will discharge lightning, unharmed,— impulses of large current lasting only a few millionths of a second. The current may be a thousand amperes or more—but the time is exceedingly short.

Any good arrester may be damaged.

—by a direct stroke—enormously high current

—by a long continued disturbance, such as an arcing ground. The current may be small but the time is long.

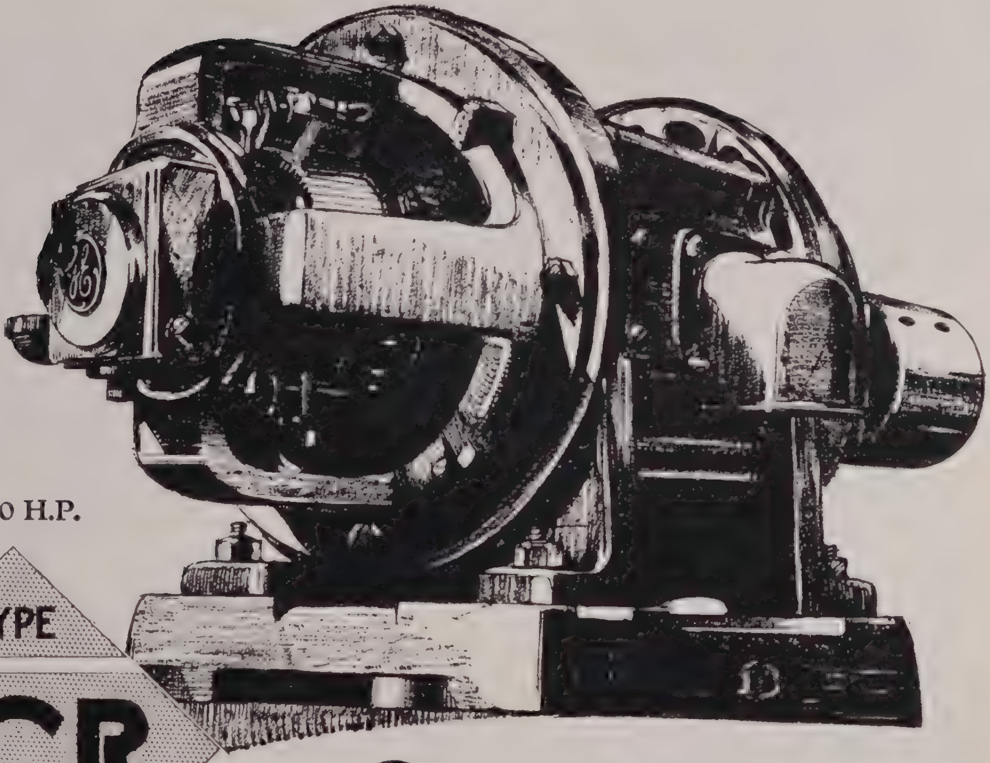
But what arrester has the best chance of discharging any disturbance, unharmed?

The arrester with the highest heat-dissipating quality. This quality is attained in the Oxide Film Arrester because of its large cell—22.7 sq. in. in area, .5 inch thick. This cell introduces weight and size, but its area is effective in discharging lightning, and its volume gives endurance to the arrester.

20-7 B

GENERAL ELECTRIC

GENERAL ELECTRIC COMPANY, SCHENECTADY, N. Y., SALES OFFICES IN ALL LARGE CITIES



Sizes
½ to 10 H.P.

TYPE
SCR
MOTOR

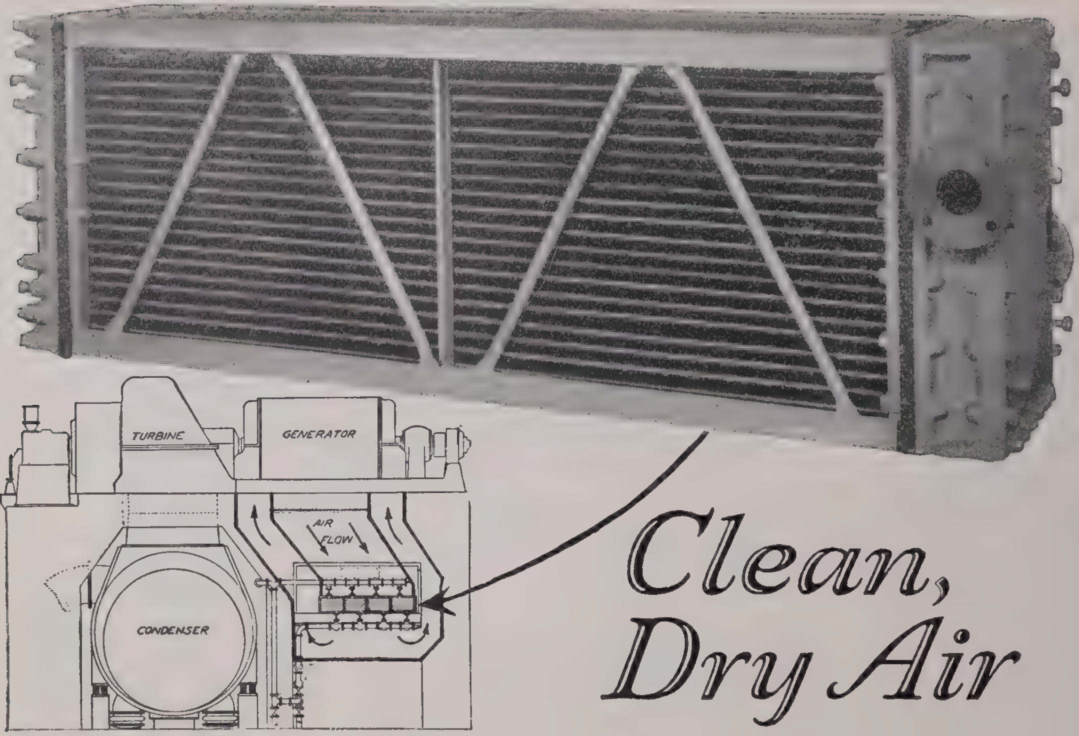
The ideal Motor for Single-Phase jobs

1. **SCR** high Starting, Accelerating and Pull Out Torque brings the load up to speed Positively and Smoothly.
2. **SCR** high efficiency and unusually high power factor result in low operating current.
3. **SCR** speed regulation is excellent—change in speed is negligible with varying load or voltage.
4. **SCR** heating is low owing to liberal rating and efficient ventilation.
5. **SCR**—quiet in starting and while running.
6. **SCR** rugged construction—large bearings and oil chambers—no complicated moving parts—these insure long life and freedom from trouble.
7. **SCR**—positive operation on low voltage.

7D-2

GENERAL ELECTRIC

GENERAL ELECTRIC COMPANY, SCHENECTADY, NEW YORK, SALES OFFICES IN ALL LARGE CITIES



Clean, Dry Air

Increase Continuity of Service with G-E Surface Air Coolers

Why tolerate generator outages that can be prevented? Generators ventilated with clean air require no shut-downs for cleaning. Hence, they insure a greater continuity of service.

The G-E Surface Air Cooler is installed in a closed system, which uses clean, dry air and recirculates it over and over. No dust or foreign particles can come in contact with the coils. The closed system provides the following other advantages:

Waste heat recovered
Less fire hazard
Simple ducts
Less noise

You can install G-E Air Coolers for existing equipment without difficulty. By all means include them in new installations.

Bulletin 45609

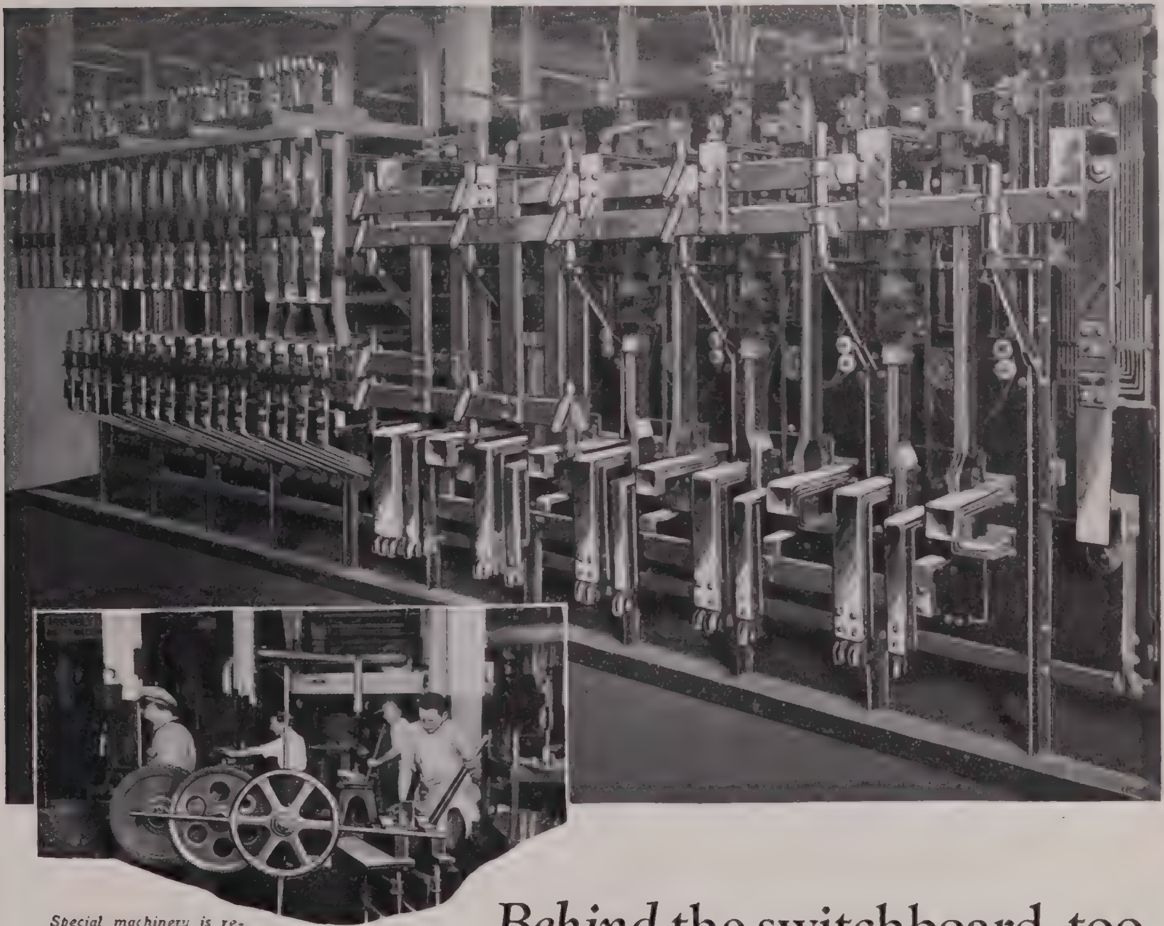
Exclusive G-E Features

- Helically wound and shouldered copper fin designed for maximum heat transfer.
- Extremely simple multi-pass water box with removable cover plate.
- Individual tubes easily removed and replaced.
- Non-corrodible, muntz-metal tube sheets, one inch in thickness.
- Sherardized bolts and frame.
- Heavy, rigidly welded, structural steel frame.
- Simple, but rigid, tube support at center of tube bank.

55-6B

GENERAL ELECTRIC

GENERAL ELECTRIC COMPANY, SCHENECTADY, N. Y., SALES OFFICES IN ALL LARGE CITIES



Special machinery is required for the best back-of-board construction.

Behind the switchboard, too, you will find G-E Quality

Good appearance is an indication of good quality.

In G-E Switchboards the workmanship not ordinarily seen must meet the same high standards that are applied to the front of the board.

Special machinery is necessary to maintain the correct clearances for bus and connection copper, to minimize the number of joints, and to shape the bars with any desired twists, off-sets, and bends, edgewise or flat, and of any angle. Adequate supports hold the busbars firmly.

The resulting symmetry and alignment of the bars facilitate installation; correct arrangement prevents excess heating; proper location provides easy accessibility.

Such refinements are characteristic of General Electric Switchboards.

23A-28.

GENERAL ELECTRIC

GENERAL ELECTRIC COMPANY, SCHENECTADY, N. Y., SALES OFFICES IN ALL LARGE CITIES

Steadfast Purpose

THE most essential element of economical production and service in any field of industry is specialization. From its earliest conception The Maqua Company was organized with a steadfast purpose in view—*Service to the electrical industry*.

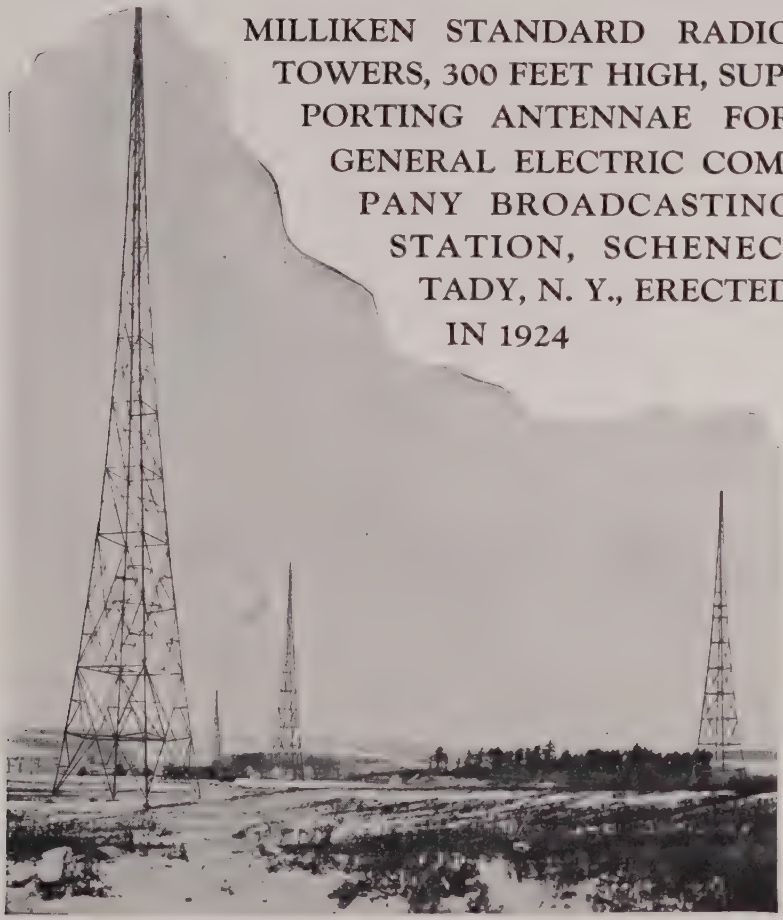
The requirements of such a clientele are exacting and wide in scope. We have been successful in meeting the demand through the untiring efforts of a force of craftsmen especially trained to produce high-grade commercial and technical printing.

For more than a decade The Maqua Company has been supplying service to manufacturers and dealers in electrical supplies and machinery. And when we mention *Service* to the buyers of printing we feel confident the word carries with it the prestige of prominence in the production of business-building printing.

THE MAQUA COMPANY

Offices and Plant located at SCHENECTADY, NEW YORK

PRINTERS, ENGRAVERS and BINDERS to the ELECTRICAL INDUSTRY



MILLIKEN STANDARD RADIO TOWERS, 300 FEET HIGH, SUPPORTING ANTENNAE FOR GENERAL ELECTRIC COMPANY BROADCASTING STATION, SCHENECTADY, N. Y., ERECTED IN 1924

MILLIKEN Standard Radio Towers, 300 feet high, are being used by the General Electric Company at its new experimental broadcasting station, Schenectady. These towers were selected by the leading broadcasting station in the world for stability, reliability, long life and economy, to secure the best results in long distance service.

The General Electric Company leads in all electrical development and specialized broadcasting equipment. This station represents the last word in experimental broadcasting.

MILLIKEN Standard Radio Towers are hot galvanized throughout. They are carried in stock for immediate shipment and are furnished in heights ranging from 66 feet to 300 feet.

Milliken towers are used also at such important broadcasting stations as—

WPG —Municipal Station, Atlantic City, N. J.
WEAF—American Telephone and Telegraph Co., New York
WSAI —United States Playing Card Co., Cincinnati
WEEI —Edison Electric Illuminating Co., Boston
WBZ —Westinghouse Electric & Mfg. Co., Springfield, Mass.
WHAZ —Rensselaer Polytechnic Institute, Troy, N. Y.
WMAF—Round Hills Radio Corporation, Dartmouth, Mass.
WCX —Detroit Edison Co., Detroit
WGBS —Gimbel Brothers, New York
WAHG —A. H. Grebe Co., Brooklyn, N. Y.

Catalogs in English and Spanish will be furnished on request.

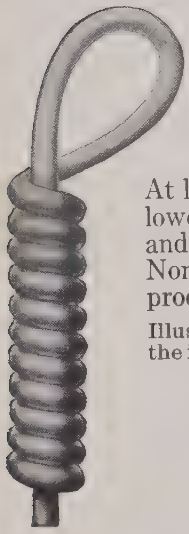
MILLIKEN BROTHERS MFG. CO., Inc.

2341 Woolworth Building - - - - New York, N. Y.

Also, Manufacturers of Transmission Towers and MILLIKEN BUILDINGS

"INDIANA"

Double Galvanized Telephone and Telegraph Wire

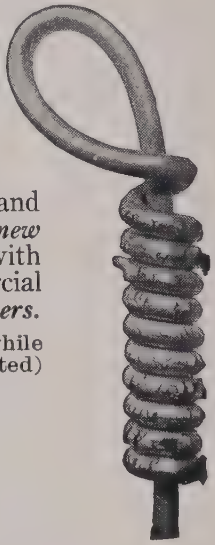


CRAPO PATENTS

Non-Peeling—Non-Cracking

At last the Telephone and Electrical Industry is assured longer life and lower maintenance on galvanized wire construction through our *new* and *improved* patented Galvanizing Process, which insures a wire with Non-Peeling and Non-Cracking Zinc Coating. Now in full commercial production. Carried in stock by Representative *Supply Jobbers.*

Illustration at right shows what happens to old process galvanizing, while the illustration at left shows assured results of CRAPO PROCESS—(patented)



Galvanized Steel Strand

Standard or Commercial, Siemens-Martin, High Strength and Extra High Strength Grades

Indiana Steel & Wire Company, - - Muncie, Indiana

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For Any Load and Any Service

Don't say the duty on your motors is too heavy for any anti-friction bearing—until you have posted yourself thoroughly on the "Hoffmann." There's a "Hoffmann" for any duty, any load, any speed—that will give you an entirely new idea of what bearing efficiency is. Tell your hardest bearing problem to our engineers and let them show you how a "Hoffmann" Roller Bearing will solve it. No obligations whatever.

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Stamford - Connecticut
PRECISION BALL, ROLLER AND THRUST BEARINGS

N 5

C. H. Wheeler Condensing Equipments

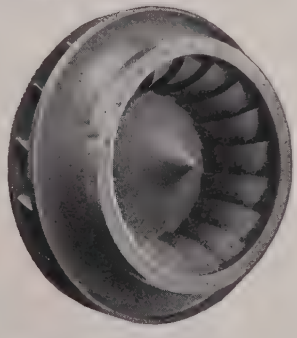
15,000-kw. Condensing Unit consisting of SURFACE CONDENSER
with "DUAL BANK" tube arrangement

TWIN AIR PUMPS with Inter and After Condenser
TWIN CENTRIFUGAL CIRCULATING PUMPS
TWIN CENTRIFUGAL CONDENSATE PUMPS

C. H. WHEELER MANUFACTURING COMPANY
Main Office and Works
Sedgley and Lehigh Avenues - - - - PHILADELPHIA, PA.
"C. H. Wheeler of Philadelphia"

PELTON

Pelton Reaction Turbine Runners



The correct design of Pelton reaction turbine runners has been proven by actual operation under most exacting conditions with heads up to 875 feet. The latter head is utilized in the Oak Grove plant of the Portland Electric Power Co., the world's highest head reaction turbine installation, where 35,000 h.p. is developed in a single unit.

Pelton engineering resources, combined with those of the associated companies, include also the most advanced designs in propeller type runners for the economical development of low heads.

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Hydraulic Engineers
2981 Nineteenth St., San Francisco 100 Broadway, New York

Associated Companies: Wm. Cramp & Sons Ship & Engine Bldg. Co., Philadelphia; Dominion Eng. Works, Montreal; Sociedade Anonyma Hilpert, Rio de Janeiro.

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Automobile Brushes
For Starting Motors and Lighting Generators.
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For Electric Furnaces.
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For Circuit Breakers.
Carbon Discs
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Carbon Specialties
For all other work.

Twenty-five Years' Experience
SPEER — the name of quality

SPEER CARBON COMPANY
ST. MARYS, PA.

Hot Weather This!

It may be possible to fan yourself with a Raw Hide Mallet

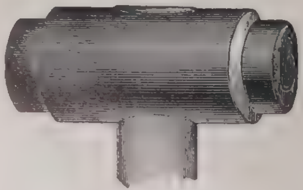
But an ounce of prevention is worth a pound of cure.

Reduce your labors and get more satisfactory results by using ***Holbrook's Hide Faced Hammers and Raw Hide Mallets*** and you will not need a fan. Ask the man who uses them. He will say: "BELIEVE ME—they are the real thing."

Manufactured by

Holbrook Raw Hide Co.

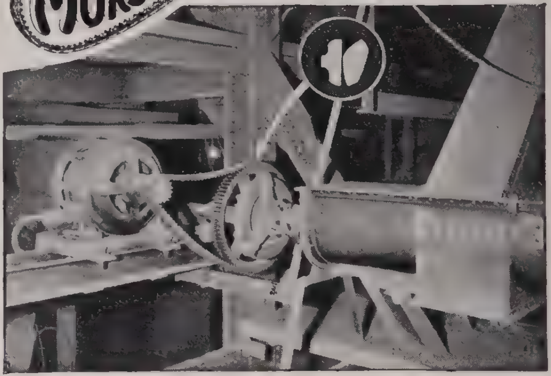
Providence, R. I.



TRADE HK MARK

Raw Hide Mallets
Hide Faced Hammers
Raw Hide Blanks for Gears

MORSE SILENT CHAIN DRIVES



Morse Chains driving from 20-h.p. G-E motors to 18-in. screw conveyors delivering grain from bleachers.

Ideal drives for limited space

Power is transmitted from motor to machine smoothly, efficiently, and quietly through Morse Silent Chains. Where available space is so limited that distance between centers must be short and in out-of-way locations which receive little attention, Morse drives assure constant service day in and day out.

Morse chains are serving practically every industry in sizes from one-quarter to 5000 h.p.

The Morse Engineer in your locality will gladly furnish complete information.

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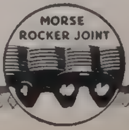
Winnipeg, Man., Can.

There is a Morse Engineer near you



478

INSIDE MICROMETER
No. 124
Set C

"Their absolute certainty—." "Always accurate." "Thoroughly dependable." That's strong language but it's taken from letters machinists have written about the Starrett No. 124 Inside Micrometer.

Ask your dealer to show it to you or write us for a copy of Catalog No. 23 "KF" describing this and 2200 other fine tools.

THE L. S. STARRETT CO.
World's Greatest Toolmakers
Manufacturers of Hacksaws Unexcelled
Steel Tapes—Standard for Accuracy
ATHOL, MASS.

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SOOT BLOWERS
for all types of boilers

Save 4 to 8% fuel.

Save labor and labor turnover.

Keep boilers on the line longer.

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POWER SPECIALTY
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Preserve your copies of the
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and at the end of the year return them to the publishers for binding - - - -

DECADE RESISTANCE BOXES

TYPE 102

General Radio Decade Resistance Boxes combine a ruggedness which will withstand the treatment of general class work with a precision of adjustment suitable for more exacting requirements.

The Ayrton-Perry method of winding is used to reduce distributed inductance and capacity.

Resistances are cut in or out by the convenient dial-switch method.

The type 102 Boxes are built with two, three, or four dials covering the range from 0.10 to 111,100 ohms.

Prices range from $25.00 to $95.00

Described in Bulletin 208G

GENERAL RADIO Co

Manufacturers of

Radio and Electrical Laboratory Apparatus

Massachusetts Avenue and Windsor Street

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No Belts
No Gears
No Electrical Connections

As applied to speed-indicators for permanent mounting, this *remarkable* statement refers *only and exclusively* to our

Frahm Vibrating-Reed Tachometers

It is merely necessary to screw the instrument (on a special bracket which we supply, if desired) to the base or other suitable part of a steam turbine, high-speed pump, generator, motor, etc., and that is *"all there is to it."*

There are no delicate internal parts—the initial accuracy is sustained during long periods of continuous service—and the cost of installation is negligible.

Write for Catalog G-1005

James G. Biddle

1211-12 Arch St., Philadelphia

The Babcock & Wilcox Co.

85 LIBERTY STREET, NEW YORK

ESTABLISHED 1868

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Water Tube Boilers
Steam Superheaters
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UNEQUALLED
PRACTICALLY PROVEN

BORNE SCRYMSER COMPANY
TURBOIL
ENDURANCE
TURBOIL
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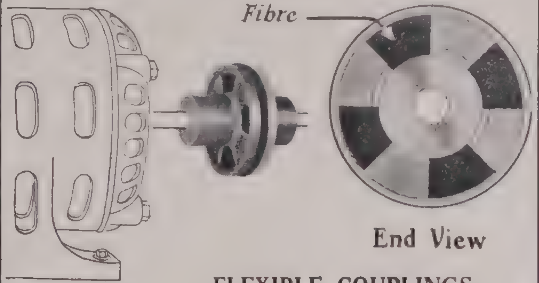
LOWEST UNIT COST
OF OPERATION POSSIBLE
CENTRAL STATION CATERING

One of its many electrical uses



FLEXIBLE COUPLINGS

—are so closely related to the electrical industry that we are illustrating the use of SPAULDING HARD FIBRE for the discs of such couplings.

This application demonstrates that SPAULDING HARD FIBRE withstands abrasion, has great mechanical strength and resists oils and greases—features that make it equally as valuable as an insulator.

Branches: New York City, Boston, Chicago, Philadelphia, San Francisco, Los Angeles, Detroit, Cleveland

Samples and prices on request

SPAULDING FIBRE CO., INC.
320 Wheeler St. Tonawanda, N. Y.

Spaulding
HARD FIBRE

USES OF FIBRE—
Do you know them?

IN building motors, generators, transformers, switchboards, trolley controls, electric elevator controls—wherever step control is used, Diamond Fibre is especially needed.

Diamond Fibre insulation has a dielectric strength of 200 to 400 volts per mil of thickness. It is dense and homogeneous. It can be sawed, punched, threaded, and turned. It does not break or crack under extreme twisting and bending.

Our automatic testing machine tests every square inch of Diamond Fibre insulation before it leaves our plant. "Spots" are plainly marked. This insures a positive means of eliminating the use of defective material.

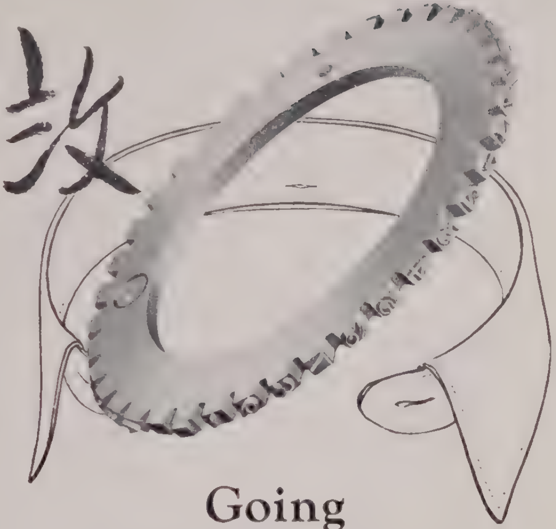
Our Engineering and Laboratory Department will gladly send you further information on request.

Diamond State Fibre Co.

Bridgeport, Pa. Chicago, Ill.
Toronto, Can.—London, Eng.

Offices in principal cities

The oldest and largest manufacturer of vulcanized hard fibre and laminated technical materials in the world.



Going
Charlie Chinaman
one better

EVERY laundry has a numbering system by which track is kept of each customer's wash. Even Charlie Chinaman uses such a system. In strange hieroglyphics by hand, he marks an identifying number in indelible ink on the inner side of every collar and the neckband of every shirt.

The modern steam laundry goes Charlie Chinaman one better. There the numbering, like the washing and ironing, is done mechanically. A machine, equipped with die-cast numbering wheels of the type illustrated, prints the serial numbers neatly, legibly and quickly.

The numbering wheel for the laundry marker is only one of many similar parts that are being die-cast by us of aluminum, zinc, lead and tin-base alloys. Included in the list are gears, disks, washers, etc., of all sizes and descriptions.

No matter how small or how large or how intricate the part you need, we are equipped to turn it out accurately, expeditiously and economically. When you buy die-castings from us, you are assured of the same high quality that has established our Dutch Boy trademark as a mark of excellence on babbitts, solder and paint materials.

NATIONAL LEAD COMPANY
Die-Casting Division
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Western Representatives: E. R. McCormick, 2599 Cadillac Ave., Detroit, Mich. A. H. Bergedick, 667 Bowen Street, Dayton, Ohio. A. A. Gildemeister, 444 Fourth Street, Toledo, Ohio.

ALUMINUM, ZINC, LEAD *and* TIN
DIE-CASTINGS

This is one of a series of advertisements describing some of the interesting and unusual uses of die-castings in various fields

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Engineers—Constructors

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Reports and Appraisals

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AJAX
Trade Mark

FIRELESS WIRELESS FURNACES

3000° C.—10 min.—carbon free

AJAX-NORTHRUP

high frequency induction furnaces.

Write for G2 and 3

Ajax Electrothermic Corporation
Trenton, New Jersey

G.H. Clamer, Pres. E. F. Northrup, Vice-Pres.

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Black and Yellow

Varnished Cambrics Varnished Paper Varnished Silk
Flexible Varnished Tubing
Insulating Varnishes and Compounds
"Cellulak" Tubes and Sheets

IRVINGTON VARNISH AND INSULATOR CO.
IRVINGTON, N. J., U. S. A.

Sales Representatives in all principal cities

For Electrical Purposes

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ALL KINDS BRAIDING SILK

William Ryle & Co.

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COMBUSTION ENGINEERING CORPORATION

PULVERIZED FUEL

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ELECTRIC
REVIEW

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Consulting Power Engineer

8 Merrimack Street

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Engineers

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Power Developments, Industrial Plants
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Engineering Construction
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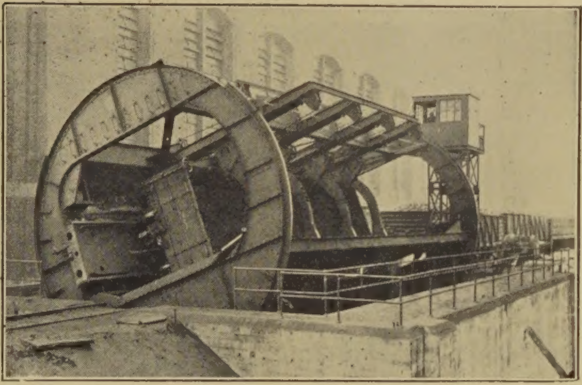
Dams Transmission Lines
Industrial Plant Construction
Superstructures as well as Substructures

120 LIBERTY STREET CITY OF NEW YORK

Offices in principal cities throughout the United States and abroad

Latest Development in Revolving Car Dumpers



It meets the demand for a dumper of simple construction, small investment, high efficiency, low operating cost and a minimum of labor.

Built in lengths of 30, 40, 50 and 60 feet for handling cars from 6 ft. 6 in. to 13 ft. 0 in. high and from 9 ft. 0 in. to 10 ft. 9 in. wide and loaded capacities up to 320,000 lbs. gross weight.

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Cleveland Electric Illuminating Co.
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The Koppers Co. for Commonwealth Edison Co. (2 Plants)
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Cleveland, Ohio, U. S. A.

Front view of Six 5-nozzle Flat-spray Clusters in operation

Close Spacing doesn't mean Crowding with

SCHUTTE KOERTING Non-clogging Flat-spray Nozzles

These nozzles produce flat fan-shaped sheets of spray. Ample air lanes between them

Ask Condenser Dept. for Bulletin 5-N

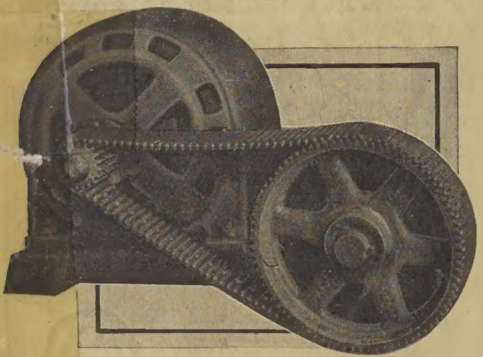
SCHUTTE & KOERTING CO., 1196 Thompson Street, Philadelphia, Pa.

Now In Stock—At Nearest Distributor

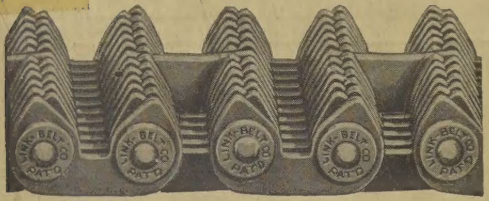
Link-Belt Silent Chain Drives

From ½ to 10 H. P.

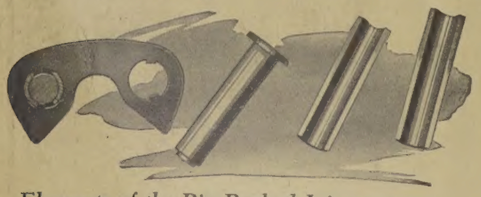
IN many cities throughout the country, it is now possible to procure Link-Belt Silent Chain Drives ranging from ½ to 10 H. P., in practically any speed ratio from 1 to 1 up to 7 to 1, at attractive prices.



The Link-Belt Silent Chain Drive is compact, durable, and 98.2% efficient (on actual test)



Middle Guide Insures the chain remaining on the wheels



Elements of the Pin-Bushed-Joint construction of Link-Belt Silent Chain. Simple and effective

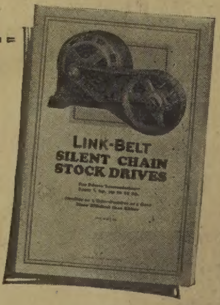
This forward step could not have been accomplished but for the knowledge and experience gained in twenty-five years of manufacturing and applying Link-Belt Silent Chain Drives.

Link-Belt Silent Chain Drive is *the* efficient connection between the motor and the driven shaft. It is 98.2% efficient (on actual test) and maintains its high initial efficiency throughout its long, trouble-free life. It is compact, maintains positive ratio, operates on long or short centers, and performs equally well in hot, cold, damp, dirty or gritty places.

Send for book No. 725 and the name of your nearest distributor.

LINK-BELT COMPANY
Box 85
INDIANAPOLIS, IND.

Please send me your Link-Belt Silent Chain Stock Drive Book as advertised.



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G.E.R.

Some Choice Territories Are Still Open For Live Distributors

LINK-BELT COMPANY, P. O. Box 85 INDIANAPOLIS

LINK-BELT

THIS YEAR LINK-BELT IS FIFTY YEARS OLD

SILENT CHAIN DRIVES